INTERNATIONAL SPACE STATION
ELECTRIC FIELD MEASUREMENT PACKAGE (EFMP)

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PREFACE

The work described in this report was performed by personnel within the Electromagnetics and Antennas Division (EAD) of the Sensors and Electromagnetic Applications Laboratory (SEAL) of the Georgia Tech Research Institute (GTRI). This task was sponsored by the National Aeronautics and Space Administration / Marshall Space Flight Center (NASA/MSFC) under Basic Ordering Agreement NAS8-97089, Contract No. H-28501D. This task was monitored by Mr. Tony Clark of NASA/MSFC. The described work was directed by Mr. John K. Daher, Project Director, under the technical supervision of Mr. David P. Millard, Chief of EAD. This report summarizes the activities and results of a concept study for an electromagnetic field measurement package (EFMP) to be flown on the International Space Station (ISS).

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1. INTRODUCTION

1.1 Background

The current radiated susceptibility test specification limit for ISS payloads is as low as 5 V/m over portions of the test frequency range [1]. Electromagnetic environmental analyses have predicted that on-orbit field strength levels, due to ground-based emitters, can be as high as 250 V/m. An Electric Field Measurement Package (EFMP) is required to determine, through experiments, the validity of these predicted levels. Validation of the on-orbit field levels will determine whether or not an increase in the radiated susceptibility test specification limits for ISS payloads is warranted.

1.2 Program Scope and Objectives

The purpose of this study was to develop an implementation plan for a flight experiment on the International Space Station (ISS) to measure the on-orbit electric field environment. The EFMP experiment will: (1) provide accurate measurement of the on-orbit electric field environment across the applicable frequency range of significant ground and ISS transmitters; (2) provide publishable measurement results and data for U.S. military and commercial spacecraft and payload developers; (3) be compatible with interface requirements (such as size and power) for an ISS external payload attach site; and (4) meet the applicable qualification requirements of ISS attached payloads. To accomplish these program objectives, the concept study consisted of the following eight tasks:

Task 1: Attend Kickoff Meeting at NASA-MSFC
Task 2: Define Electric Field Measurement Requirements
Task 3: Assess Electric Field Measurement and Recording Technology
Task 4: Explore Alternate Experimental Concepts
Task 5: Define Interface Requirements
Task 6: Define Qualification Requirements
Task 7: Select Preferred Measurement Package Concept
Task 8: Prepare Implementation Plan

2. KICKOFF MEETING AT NASA/MSFC

On 26 August 1997, GTRI and NASA/MSFC personnel met in Huntsville, AL. The meeting consisted of the following: (1) technical discussions related to the desired performance of the EFMP; (2) an overview presentation of the EXpedite the PRocess of Experiments to Space Station (EXPRESS) pallet system for external payloads; (3) a brief discussion of the proposed Environmental Monitoring Package (EMP); and (4) a review of proposed program tasks/ schedule for the EFMP Concept Study. NASA personnel also provided GTRI engineers with an informal tour of their EMI test facilities and ISS assembly areas, as well as reference documentation.

During technical discussions, NASA personnel provided GTRI with the ISS orbital parameters including the inclination, altitude (minimum and nominal), and orbital period. NASA personnel also indicated that they are particularly interested in verifying the on-orbit field levels produced by UHF and C-Band emitters that are part of the Space Surveillance Network (SSN). This would require the measurement package to provide frequency information (at a minimum for these two bands). The desired configuration for the system is to mount the antenna/sensors externally. However, if necessary, there is an earth-pointing window on the ISS through which an internally mounted antenna could be pointed. The EXPRESS pallet system is being developed to modularize all external payloads for ease of implementation. EXPRESS pallet discussions focused on size and electrical interface constraints for a modularized EXPRESS pallet payload. Also, NASA is developing an Environmental Monitoring Package (EMP) payload for the ISS. It was initially recommended that the possibility of integrating the Electric Field Monitoring Package with the EMP should be explored. However, it was later learned that the conceptual payload design for the EMP was due 1 September 1997. Therefore, if the integration with the EMP takes place, it will have to be done as part of the pre-planned product improvements (P3I) program.

During the meeting, GTRI obtained a number of documents [2-8] that proved to be very useful in completing the various tasks on this program. Finally, it is noted that NASA personnel were in complete concurrence with the proposed program plan for the EFMP Concept Study and had no recommended changes to the proposed program tasks or schedule.

3. ELECTRIC FIELD MEASUREMENT REQUIREMENTS DEFINITION

The objective of this task was to determine fundamental design requirements for the EFMP. The EFMP design requirements consist of the following: (1) frequency range/resolution; (2) sensitivity; (3) dynamic range; (4) sensor/antenna performance; (5) electric field sampling rate; (6) electric field data recording rate; and (7) number of orbits required to collect the requisite data. It is important that that the system design requirements be tailored to optimize the measurement of the expected on-orbit electric field environment. Therefore, as part of this task, GTRI reviewed the relevant documentation [9,10] to determine the expected ISS on-orbit electric field environment. Reference 9 defines the expected electric field environment produced by terrestrial emitters for orbital ranges of 100 to 2,000 nmi. Reference 10 contains RF output power data for transmitters that will be located on-board the ISS and the shuttle orbiter. The design requirements for the EFMP were based primarily on the predicted electric field environment as specified in these reports.

During the program kickoff meeting at NASA/MSFC, NASA personnel stated that the primary goal of the EFMP is to measure the field levels produced at the ISS orbital altitude by terrestrial emitters and that measuring field levels from ISS on-board transmitters are of lower priority. Thus, the data in Reference 9 was of primary interest for this task. In particular, the worst-case field strength plot contained in Reference 9 (page A-10) for a 200 nmi orbit was used as a guide for defining the desired frequency range/resolution, sensitivity, and dynamic range requirements for the EFMP. The data in the Reference 10 was used to determine the frequency range and power levels of on-board transmitters. NASA is particularly interested in measuring the field levels produced by radars that comprise the U.S. Space Surveillance Network (SSN).

3.1 The United States Space Surveillance Network

The mission of U.S. SSN is to detect, track, catalog, and identify all man-made objects in space [9]. The network is comprised of dedicated, collateral, and contributing sensors distributed about the earth. The primary mission of dedicated sensors is to support the SSN in maintaining the catalog of artificial satellites and supporting a host of space operations. Although the primary mission of collateral sensors, which include 12 major radars, is ballistic missile attack warning and/or intelligence gathering, these sensors actually provide a significant share of U.S. space surveillance observations. Finally, contributing sensors are owned and operated by other Agencies but provide space surveillance data under special agreements or contracts. The radars which comprise the U.S. SSN are listed in Table 1 [9,12]. According to Reference 12, the transmit polarization for these radars are all either linear (typically vertical) or right-hand-circular (RHC).

3.2 ISS Orbital Parameters

The ISS will orbit the earth at a nominal altitude of approximately 200 nmi (150 nmi minimum altitude) and an inclination of approximately 51.6°. The nominal orbital period is 90 minutes. SSN radar site locations along with typical orbital ground tracks for a 90 minute orbital period and a 60° orbital inclination are shown in Figure 1 [9]. The contour lines in the figure represent line-of-sight intercepts for a 200 km altitude (line-of-sight coverage for the 200 nmi

TABLE 1. UNITED STATES SPACE SURVEILLANCE NETWORK RADARS [9,12]

FREQ. BAND	SENSOR TYPE	SYSTEM	LOCATION	OP AGENCY	OP FREQ. (MHz)	ALT.[1]	AZIMUTHAL COVERAGE (deg)	SSN CATEGORY
VHF	Interfer-ometer	NAVSPASUR	CONUS (32.6N,243.OE) (33.4N.,253.0E) (33.3N,266.4E) (33.1N.,269.0E (32.3N,276.5E) (32.0N,278.1E)	USN	217	LEO HEO	90,270	DEDICATED
VHF	DISH RADAR	ALTAIR	ROI-NAMUR IS. (09.4N,167.5E)	USA	153-162	LEO	0-360	CONTRIBUTING
UHF	DISH RADAR	BMEWS II (AN/FPS-92)	ALASKA (64,3N,210.SE)	USAF	400-450	LEO	0-360	COLLATERAL
UHF	DISH RADAR	ALTAIR	ROI-NAMUR IS. (09.4N,167.5E)	USA	415-440	LEO HEO	0-360	CONTRIBUTING
UHF	PHASED ARRAY RADAR	BMEWS I (AN/FFPS-120)	GREENLAND (79,6N,291.7E)	USAF	420-450	LEO	0-360	COLLATERAL
UHF	PHASED ARRAY RADAR	BMEWS III (AN/FPS-126)	ENGLAND (54.4N,359.3E)	RAF	420-450	LEO	0-360	COLLATERAL
UHF	PHASED ARRAY RADAR	EGLIN (AN/FPS-85)	CONUS (30,6N,273.8E)	USAF	NA	LEO HEO	120-240	DEDICATED
UHF	PHASED ARRAY RADAR	PARCS (AN/FPQ-16)	CONUS (48.7N,262.1E)	USAF	NA	LEO	298-360 0-078	COLLATERAL
UHF	PHASED ARRAY RADAR	PAVE PAWS E (AN/FPS-123)	CONUS (41.8N.289.5E)	USAF	420-450	LEO	347-360 0-227	COLLATERAL
UHF	PHASED ARRAY RADAR	PAVE PAWS W (AN/FPS-123)	CONUS (39.1N,2387.6E)	USAF	420-450	LEO	126-360 0-227	COLLATERAL
C	DISH RADAR	ALCOR	ROI-NAMUR IS. (09.4N,167.5E)	USA	5664-5672	LEO	0-360	CONTRIBUTING
C	DISH RADAR	ANTIGUA (AN/FPQ-14)	ANTIGUA IS. (17.1N,298.2E)	USAF	5400-5900	LEO	0360	CONTRIBUTING
C	DISH RADAR	ASCENSION (ANFPS-15)	ASCENSION IS. (07.9N298.2E)	USAF	5400-5900	LEO	0-360	COLLATERAL
C	DISH RADAR	KAENA POINT (AN/FPQ-14)	HAWAII (21.6N,201.7E)	USAF	5400-5900	LEO	0-360	COLLATERAL
L	DISH RADAR	MILLSTONE HILL	CONUS (42.6N,288.5E)	MIT	1295	LEO HEO	0-360	CONTRIBUTING
X	DISH RADAR	HAYSTACK LRIR	CONUS (42.6N,288.5E)	MIT	10000	LEO HEO	0360	CONTRIBUTING
Ku	DISH RADAR	HAYSTACK AUXILIARY RADAR (HAX)	CONUS (42.6N,288.5E)	MIT	16,700	LEO HEO	0-360	CONTRIBUTING

Note 1: LEO = Low Earth Orbit HEO = High Earth Orbit

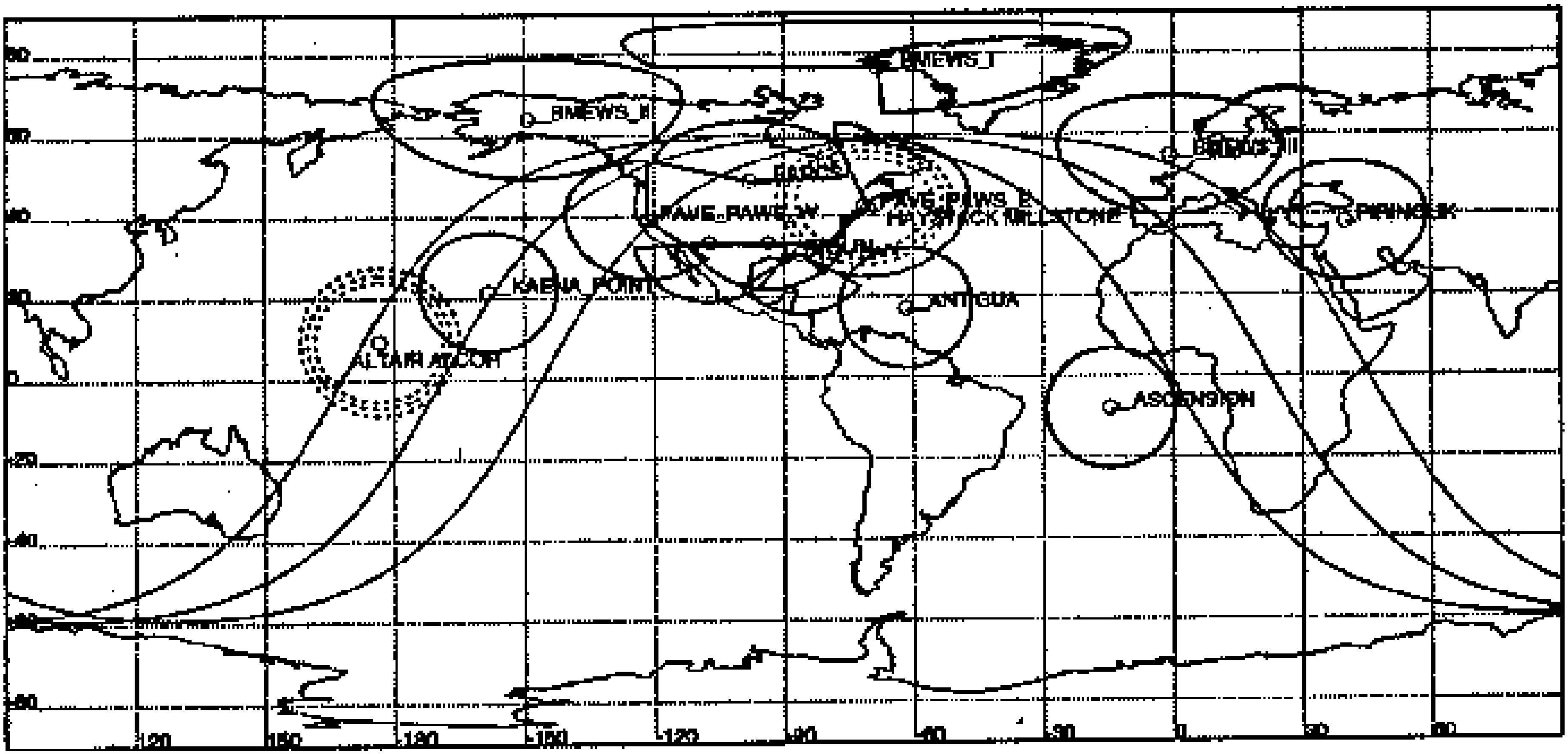

Figure 1. U.S. Space Surveillance Network Site Locations and Orbital Ground Tracks (90 minute orbital period, 60° inclination) [9].

ISS orbital altitude would be somewhat larger). A 10 degree minimum elevation angle is assumed for the ground radars.

3.3 Frequency Range/Resolution Requirements

The frequency range requirement is defined to be 100 MHz to 18 GHz. The lower frequency range requirement of 100 MHz is selected to enable detection of Russian space surveillance radars, many of which operate in the VHF band. The frequency range requirement covers all emitters of interest in the Reference 9 except the 35 and 95.5 GHz instrumentation radars located at Roi-Namur in the Marshall Islands. It is GTRI's judgment that: (1) very few EMI problems are generated by millimeter wave emitters due to the high susceptibility thresholds of electronic devices and the small coupling cross-sections of receptors at these very short wavelengths and (2) a measurement package design that included these Ka and W-Band frequencies would be cost prohibitive when compared with the limited additional data that would be collected at these bands.

3.4 Sensitivity Requirements

The sensitivity requirement is defined to be 2 V/m. The 2 V/m system sensitivity level is considered an adequate lower limit for detecting field levels that will be of interest. Currently all ISS payloads must meet a minimum radiated susceptibility test requirement of 5 V/m [1]. Thus, the 2 V/m measurement package sensitivity level will allow adequate margin for evaluating this payload susceptibility limit in the ISS operational environment.

3.5 Dynamic Range Requirements

The minimum dynamic range requirement is defined to be 42 dB. Based on Reference 8, the highest expected field strength at 200 nmi is approximately 250 V/m. With a desired sensitivity of 2 V/m, the minimum dynamic range requirement is readily calculated to be 42 dB (i.e., 20log[250/2]). Additional dynamic range would provide for greater signal detection capability and additional flexibility in the design of the measurement package. Dynamic range is limited on the high end by possible saturation and damage of the receiver front end. The low end of the dynamic range is primarily limited by antenna sensitivity and receiver noise figure.

3.6 Sensor/Antenna Performance Requirements

The remaining design requirements (sensor/antenna performance, frequency resolution, electric field sampling rate, electric field data recording rate, and number of orbits required to collect data) will vary depending on the measurement technique that is used to implement the measurement package system. Sensitivity, dynamic range, and frequency resolution requirements make the use of a frequency scanning superheterodyne receiver (e.g., a spectrum analyzer) an attractive measurement instrument. Therefore, it is reasonable to determine the sensor/antenna performance, frequency resolution, electric field sampling rate, electric field data recording rate, and number of orbits requirements assuming an implementation of this type of measurement system.

The antenna factor (AF) requirement is specified to be 31–70 dB/m. To allow for design flexibility, this AF specification is to include any cable losses or external attenuation between the antenna and the receiver input. Antenna factor, which is defined as the ratio of the incident field strength to the induced antenna voltage, is a convenient parameter for use in specifying the antenna performance. The minimum AF of 31 dB/m was determined based on the maximum anticipated field strength (250 V/m) and the maximum allowable input level to the receiver (typically 1 W or approximately 7 V into 50 Ω). The maximum allowable AF of 70 dB/m was determined from the sensitivity requirements of the EFMP. Broadband antennas with AFs in the 30-70 dB/m range will have sufficiently broad beamwidths to cover the solid angle subtended by the earth's surface at a 200 nmi orbit.

Appendix A contains a Mathcad® model which was developed to calculate the maximum allowable AF (and, equivalently, the minimum required antenna gain) to meet the measurement sensitivity requirements. Inputs to the model include the following: the frequency range and the number of points to be used for the calculations; the total amount of RF attenuation (both internal and external); the receiver IF bandwidth and noise figure; the antenna temperature; the minimum signal-to-noise ratio (S/N); the minimum electric field sensitivity; and the coaxial cable parameters (length, geometry, dielectric constant and power factor, and conductor material parameters). Based on the 2 V/m sensitivity requirement and a typical worst-case spectrum analyzer noise level of -61 dBm (as measured for an HP 8566B spectrum analyzer with a resolution bandwidth of 3 MHz); the AF could not exceed 70 dB to maintain a minimum S/N of 10 dB. Again, the 70 dB/m AF specification includes any RF cable losses or external attenuation between the antenna and the receiver (e.g., as seen in Appendix A, with 10 dB of cable loss, the AF could not exceed 60 dB/m).

The optimum antenna solution to ensure coverage of all incident signal polarizations (i.e., eliminate polarization mismatch losses for all possible signal polarizations) is to use dual, orthogonally polarized antennas. Examples include a dual polarized, log-periodic dipole array or one RHCP and one left-hand-circularly polarized (LHCP) conical log spiral antenna. The total field level can be determined by performing separate measurements for each polarization and then appropriately adding the orthogonal polarization electric field components (i.e., calculating the square root of the sum of the squares) as part of the post-measurement data calibration process.

3.7 Resolution Bandwidth Requirements

The EFMP should at the least have sufficient frequency resolution to discriminate between emissions in broad frequency bands of interest (e.g., as a minimum, upper VHF, lower UHF, L, S, C, X, and Ku bands). The majority of the SSN radar systems operate in the lower UHF band (400-450 MHz) or C-Band (5400-5900 MHz). Measurement of field levels in these two frequency bands should therefore be given a high priority in the design of the EFMP. Better frequency resolution (on the order of a few MHz) is highly desirable. However, narrowing the frequency resolution beyond this point will reduce measurement sensitivity and accuracy when measuring signals from narrow pulse width emitters.

Most of the high power emitters of interest are pulsed radars. Based on the data contained in NASA Contractor Report 4776, the pulse repetition frequencies (PRFs) and pulse widths for these radars are in the ranges of 0.1 to 400,000 pulses per second and 0.03 to 50,000 μs, respectively. The goal of the measurement system is to measure the peak field level of these radars. If the impulse bandwidth of the receiver is greater than the reciprocal of the pulsewidth of the radar signal, then the receiver will detect the peak amplitude of the pulse. For narrower impulse bandwidths, the peak response of the receiver is a function of the product of the pulse width and impulse bandwidth. Under these conditions, the amplitude reduction of the detected signal level in dB relative to the actual peak pulse level is approximated by:

$$L_p = 20 \cdot \log(B_i \cdot t) \qquad \textbf{(1)}$$

where:

L_p = amplitude loss in dB;
τ = pulsewidth of the measured signal; and
B_i = impulse bandwidth of the receiver.

For spectrum analyzers that specify 6 dB resolution bandwidths, the resolution bandwidth is nearly equal to the impulse bandwidth. Thus, the amplitude loss can be made to equal zero if the product of the pulsewidth and resolution bandwidth can be made to be greater than or equal to one. The maximum resolution bandwidth for typical spectrum analyzers is in the range of 3 MHz. Thus, peak field levels for radars with pulsewidths greater than 0.33 μs can be detected without significant loss. All but seven of the emitters surveyed in the NASA Contractor Report 4776 have pulsewidths greater than 0.33 μs. Resolution bandwidths greater than about 5 MHz result in little improvement in pulse response for the emitters of interest while reducing the frequency measurement accuracy and the receiver sensitivity to continuous wave (CW) or long pulse width signals. Resolution bandwidths much less than 1 MHz result in degraded pulse response. Thus, the recommended resolution bandwidth is 3 MHz.

3.8 Electric Field Sampling and Data Recording Rates

In the calculations of receiver frequency scan rates, it is assumed that the ISS (and thus the receiver) is being tracked by the terrestrial radar. One approach to sampling the electric field strength from these pulsed radars with a scanning receiver is to scan in frequency slow enough to insure that no pulses go undetected. This approach will be called the “slow scan” approach. If the resolution bandwidth requirement is set at 3 MHz, the required electric field sampling rate (expressed as the inverse of the spectrum analyzer’s sweep time) can be calculated. The majority of the radars surveyed in the NASA Contractor Report 4776 have PRFs greater than 100 Hz. Thus, the equivalent pulse repetition interval is 0.01 s or less. To ensure that signals with pulse repetition intervals less than 0.01 s (PRFs greater than 100 Hz) are detected by the scanning spectrum analyzer, the time that any given frequency is within the passband of the resolution filter must be at least 0.01 s. Thus, the corresponding sweep time constraint can be expressed as:

$$ST \geq \frac{SR}{BW_r \cdot PRF_{\min}} \quad \text{(slow scan approach)} \qquad \textbf{(2)}$$

where:

ST = receiver sweep time (time for full sweep);
SR = receiver sweep range (frequency band over which the receiver sweeps);
BW_r = receiver resolution bandwidth; and
PRF_{min} = minimum radar pulse repetition frequency.

Covering the 100 MHz to 18 GHz frequency range requires a total SR of 17.9 GHz (which with an HP 8566B spectrum analyzer would require four sub-bands having bandwidths of 100 MHz to 2.5 GHz; 2.5 GHz to 5.8 GHz; 5.8 GHz to 12.5 GHz; and 12.5 GHz to 18.0 GHz). With the spectrum analyzer resolution bandwidth set at 3 MHz; the minimum scan time that would be required to ensure that all pulsed signals with PRFs greater than 100 Hz are detected is approximately 60 s. However, sampling two orthogonal electric field polarizations with a single receiver will require a total frequency scan time of approximately 120 s. Thus, approximately 1/120 Hz or 8.3 millihertz (mHz) will be defined as the maximum electric field sampling rate. If a faster sampling rate is required for particular sub-bands (e.g., during particular portions of the orbit), the scan range for those particular sub-bands can be reduced. In this way, the measurement package would have the capability to scan narrow sub-bands to accommodate the efficient collection of data for specific emitters of interest. The electric field data will likely be stored to an electronic file at the completion of each scan. Thus, the data sampling rate (for all frequencies in each band) will have a maximum rate of somewhat less than 8.3 mHz (allowing for overhead time of approximately 1 second to store each trace corresponding to an orthogonal field polarization). For minimum sampling rate specifications, we will select a minimum electric field sampling rate and a minimum data sampling rate of 8 mHz.

An alternate approach, which we will call the “fast scan” approach, would be to use the “MAX HOLD” feature of the spectrum analyzer to display the maximum detected amplitudes from a number of sweeps using a relatively fast sweep rate before storing the trace. With this approach, radar pulses could be missed if the ST is a harmonic or a sub-harmonic of the radar pulse repetition interval (1/PRF). Thus, the STs would have to be carefully selected and/or multiple STs would have to be used on alternate scans to insure a high probability-of-intercept (POI). (Note that an intercept becomes a detection only if the intercepted signal strength exceeds the detection threshold sensitivity of the receiving system.) With the fast scan approach, the electric field sampling rate would be significantly higher than the slow scan approach outlined above. However, the data sampling rate would likely be comparable to that of the slow scan approach since a number of frequency scans would have to be made to ensure an acceptably high POI. A Mathcad® model that calculates the measurement time required to achieve a desired POI using the fast scan approach is provided in Appendix B.

3.9 Number of Orbits Required to Collect the Data

Based on a nominal 90 minute orbital period, successive ground tracks will be separated by approximately 22.5 degrees in longitude (see Figure 1). With an orbital inclination of 51.6 degrees and a 200 nmi orbital altitude, all SSN emitters with latitudes between approximate 65 degrees N and 65 degrees S should be able to have line-of-sight (LOS) visibility to the ISS. Of the 17 radars that make up the U.S. SSN, only one (BMEWS I) will not have LOS visibility to the ISS.

SSN radar metric observations include time, elevation, azimuth, range, and possibly range rate [10]. Three to five metric observations are typically made per track and six to ten seconds are typically required per metric observation. Thus, track times are expected to be in the 18-50 second range. As detailed in Section 3.7, spectrum analyzer scan times of approximately 60 seconds per polarization (or 120 seconds total for two orthogonal polarizations) are required to scan the entire 100 MHz to 18 GHz frequency range. However, spectrum analyzer scan times can readily be reduced below 18 seconds while still ensuring intercept of radar pulses by narrowing the scan frequency range about the known operating frequency of the tracking radar. Also, longer track times could presumably occur provided that special arrangements are made in advance. In either case, if the ISS is tracked by a SSN radar, it can be assumed that electric field data can be collected from that SSN radar.

According to Reference 10, standard procedure for tracking the ISS would consist of at most a single SSN radar track per orbit (provided LOS visibility exists). Furthermore, without special arrangements being made, it is likely that certain SSN assets would be used to track the ISS more often than other assets. For example, all else being equal, UHF phased array radars would likely be the asset of choice (in favor of UHF or C band dish radars) due to the higher achievable data rates. With 16 radars in the U.S. SSN with LOS visibility to the ISS and without special arrangements being made to ensure that specific assets are used to track the ISS, an inordinately high number of orbits would be required to ensure that all SSN radar emissions are characterized. Thus, it is assumed that special arrangements will be made in advance of the experiment to allow for tracking of the ISS with specific radars during specific times and orbits and, if desired, tracking of the ISS by more than one SSN radar in a single orbit. Assuming that these prior arrangements will be made and allowing for the possibility of some orbits in which the ISS will not be visible to a SSN radar or will only be visible to a radar which has already be characterized, it is estimated that a minimum of about 10 orbits will be required to characterize the emissions from the SSN. A greater number of orbits are desirable to provide better statistical data on SSN radars and other emitters.

3.10 Summary of Electric Field Measurement Requirements

The EFMP design requirements defined under this task are summarized below (sampling rates based on slow scan approach):

(1) Frequency Range: 100 MHz to 18 GHz
(2) Sensitivity (min): 2 V/m
(3) Dynamic Range (min): 42 dB (2 V/m – 250 V/m)
(4) Antenna Factor (including cable losses and external attenuation): 31 - 70 dB/m
(5) Resolution Bandwidth (nom): 3 MHz
(6) Electric Field Sampling Rate (min): 8 mHz
(7) Data Sampling Rate (min): 8 mHz
(8) Number of Orbits (min): 10

These design requirements are idealized requirements that have been defined to guide the design of the measurement package system. Based on the analyses performed under this task, it is believed that these design requirements are adequate to meet the baseline objectives of the experiment and are achievable with commercial off-the-shelf (COTS) hardware. However, it should be emphasized that these requirements may be relaxed or strengthened as desired in order to achieve a lower cost or higher performance design, respectively.

4. ELECTRIC FIELD MEASUREMENT AND RECORDING TECHNOLOGY ASSESSMENT

The objective of this task was to perform a survey to determine the current state of the technology and hardware that will be required to implement the EFMP (based on the requirements specified in Task 2). The primary focus of this survey was to determine the feasibility of designing the measurement package using available COTS hardware. Utilization of COTS hardware can significantly reduce the development time and cost. This survey was performed by reviewing hardware manufacturer's literature (catalogs and internet sites), technical papers, and trade journal articles. The major hardware components required to implement the measurement package are antennas/sensors, a spectrum analyzer, a computer, data network interface adapters, and a power supply/converter (to interface to the space station power system). During this survey, typical cost, size, weight, and power consumption for these components were identified and this information was factored into design feasibility considerations.

The antenna/sensor technology survey focused on the following three technologies: (1) broadband resistive dipole sensor systems; (2) electro-optic sensor systems; and (3) RF antenna technology. All of these technologies are established and commercially available. Other electric field sensing technologies such as thermo-optic, acousto-optic, and magneto-optic sensors are still in the development stages and were not found to be commercially available. Therefore, these technologies were dismissed from further consideration.

Broadband resistive dipole sensors typically consist of three-axis, tapered resistive dipole elements with three diode detectors and A/D converters integrated into a single sensor package. The electronics in the package are powered with a rechargeable battery. The probes are small (typically less than 18 inches long and four inches wide) and weigh approximately one pound. Individual probes that cover the 100 MHz – 18 GHz frequency range (frequency range specified in Task 2) are commercially available. The probe is usually interfaced with a controller/display unit via a fiber optic link. Typical sensitivities for these systems are 1-300 V/m and they have sampling rates between 1-24 samples per second. However, since the signal is detected at the dipole output, these systems provide no frequency information. Furthermore, their slow response times typically result in integration of pulsed fields rather than measurement of peak field levels. Based on these drawbacks, this type of system was not selected for the EFMP.

Electro-optic field sensing systems have undergone rapid development within the last five years and can be purchased as an integrated package or assembled from commercially available components. Electro-optic systems consist of a Mach-Zehnder optical modulator, laser light source, photo-detector, and attached antenna element. The laser light source and photo-detector are connected to the optical modulator via fiber optic cables. The modulator is an interferometric system in which the optical power output varies with the voltage supplied from the antenna element. The output of the photo-detector is typically fed into a pre-amplifier and the output from the pre-amplifier is measured with a spectrum analyzer. A recent paper [11] has reported that the frequency range of 50 MHz to 18 GHz can be covered using only two modulators (and antenna packages). Sensitivities as low as 1 mV/m were recorded. However, the linearity of the modulator starts to compress above 10 V/m. On-orbit field strengths are predicted to be as high as 250 V/m, thus this system would not have sufficient dynamic range. Electro-optic sensors can also have thermal sensitivities which can induce large measurement error unless precise thermal compensation is applied [12]. These drawbacks led to GTRI eliminating this type of system from further consideration for use in the measurement package. GTRI thus recommends a simple complement of standard RF antennas coupled to a spectrum analyzer to best meet the needs of the EFMP.

The review of RF antenna technology focused on minimizing the number and size of the antennas required to cover the 100 MHz to 18 GHz range. A review of COTS antennas indicated that a minimum of two antennas are required to cover the 100 MHz to 18 GHz frequency range. The optimum antenna solution to ensure coverage of all incident signal polarizations (thus eliminating polarization mismatch losses for all possible signal polarizations) is to use a dual, orthogonally polarized antenna or two orthogonally polarized circular antennas (i.e., one RHC and one LHC polarization antenna). Examples include RHC or LHC conical log spirals which cover the range of 100 MHz to 1 GHz and dual, linearly polarized log periodic dipole arrays which cover the range from 1-18 GHz. The total field level can be determined by performing separate measurements for each polarization and then appropriately adding the orthogonal polarization electric field components (i.e., the square root of the sum of the squares) as part of the post-measurement data calibration process. The drawback to this method is that the measurement scan time will be doubled. Size is the primary constraint, particularly for the lower frequency broadband antenna. [NOTE: Due to payload size constraints, a COTS orthogonally polarized antenna set covering the 100 MHz to 1 GHz range could not be identified for the final recommended measurement package configuration. See Section 4.2 of the measurement package implementation plan for antenna design trade-off details.]

Portable spectrum analyzers that meet the requirements of the EFMP are available from both Hewlett-Packard and Tektronix. These spectrum analyzers typically take up less than one cubic foot of space and weigh less than 45 pounds. They come with IEEE-488 (GPIB) and/or RS-232 data interface connections. Costs range from $20,000 to $30,000 depending on the options included. Power consumption ranges from approximately 200 to 500 VA.

A portable computer can be used in the measurement package as a system controller and to provide a data interface between the spectrum analyzer and the ISS data links. The computer can interface with the spectrum analyzer via a GPIB link and with the ISS via an Ethernet link. Small, portable notebook or laptop computers are available from numerous manufacturers. These computers typically weigh less than 10 pounds and consume less than 50 watts of power. Costs are typically less than $5,000. Also, IEEE-488 and Ethernet adapter PCMCIA cards for portable computers are available from many sources with costs ranging from $100 to $300. In addition, Ethernet GPIB controller modules are commercially available which allow remote GPIB control of an instrument (such as a spectrum analyzer) via an Ethernet connection. Typical cost for these modules is approximately $1,000 and weight is approximately one pound.

The ISS supplies power on 120 Vdc and 28 Vdc buses. The spectrum analyzers considered in this survey require a 120 Vac input to operate. Numerous companies manufacture 28 Vdc to 120 Vac, 60 and 400 Hz inverters for aircraft operations. The portable Hewlett-Packard analyzers reviewed during this survey are specified to operate at 120 Vac over a 47-440 Hz frequency range. Thus, these particular spectrum analyzers should work with a 400 Hz inverter as well as a 60 Hz inverter. An inverter with the capacity (up to 500 VA) to power the measurement package was identified which weighs approximately four pounds and take up a volume of less than 0.25 cubic feet. Costs for single-phase inverters typically range from $2,000 to $20,000, depending on the required power and environmental specifications. The measurement system's portable computer could be powered by replacing the AC-to-DC power supply that is provided by the computer manufacturer with a DC-to-DC power supply that is compatible with the ISS power bus voltages. DC-to-DC converters that can perform this function are manufactured by numerous companies.

5. ALTERNATE EXPERIMENTAL CONCEPT EXPLORATION

The purpose of this task was to evaluate various experimental concepts and to determine the approach that is best suited to the EFMP objectives. NASA personnel have indicated that a primary objective of the measurement package should be to verify the on-orbit field levels of terrestrial based radars (in particular radars that comprise the space surveillance network). NASA also desires that data be collected within reasonably narrow frequency bands (e.g., as a minimum, upper VHF, lower UHF, L, S, C, X, and Ku bands). During Tasks 2 and 3, it was determined that a system utilizing a scanning superheterodyne receiver (COTS spectrum analyzer) can be implemented to detect the peak field levels and provide frequency information for the majority of the terrestrial transmitters of interest. This measurement package configuration is best suited to NASA's data collection objectives.

However, the following two measurement issues needed to be resolved: (1) maximizing the probability of intercept of signals of interest and (2) tradeoffs between external or internal location of the measurement package. As part of Task 2, GTRI proposed two alternate measurement procedures which were termed the "slow scan" approach and the "fast scan" approach. The slow scan approach is designed to ensure intercept (and detection if the signal level exceeds the EFMP sensitivity level) of pulsed signals with PRFs greater than some minimum value. This approach requires a minimum scan time of 60 s to intercept all pulsed signals with PRFs exceeding 100 Hz in the frequency range of 100 MHz to 18 GHz. This scan time will be doubled if dual polarized antennas are used and each orthogonal polarization is scanned separately. The fast scan method would use the MAX HOLD feature of the spectrum analyzer to display the maximum detected amplitudes from a number of sweeps using a fast sweep time before storing the trace. An analysis of the fast scan approach was completed and the POI was determined as a function of the emitter parameters (pulse width and pulse repetition interval (PRI)), the spectrum analyzer parameters (scan range, resolution bandwidth, and scan time), and the measurement (or observation) time. The details of this analysis are included in Appendix B. For a specified (desired) POI, the required measurement time can be extremely large (theoretically infinite) if the receiver sweep time is close to a harmonic or a sub-harmonic of the radar PRI. Thus, if the fast scan approach is used, the sweep times would have to be carefully selected and/or multiple sweep times would have to be used on alternate scans to insure a high POI. This approach can potentially shorten the measurement time provided some reduction in POI is accepted. The slow scan approach provides a POI of 100% whereas, in effect, the fast scan approach trades off POI for reduced measurement time.

The external EXPRESS system has no provision for a dedicated analog RF link. Thus, there does not appear to be any practical method for locating the measurement package antennas external to the ISS and then connecting the antennas via an RF cable to a spectrum analyzer measurement receiver that would be located internal to the ISS. It appears that the only two viable options for location of the measurement package are to either (1) package the entire system as an external EXPRESS pallet payload and to collect data via the data links (Ethernet or MIL-STD-1553B bus) provided by the EXPRESS system or (2) locate the entire system inside the U.S. laboratory module of the ISS and package the experiment as a Nadir window facing experiment (antennas pointing through the Nadir window). The basic tradeoffs between these two experimental concepts were investigated.

From a measurement accuracy viewpoint, it is preferable to locate the measurement package antennas externally as part of a Nadir facing payload package. However, as mentioned previously, location of the antennas outside of the ISS requires that the entire measurement package be located externally. Location of the complete system outside of the ISS requires that the package operate and survive in the harsh natural space environment. A preliminary investigation was conducted to determine the potential environmental hardening measures that are likely to be required to enable the measurement package to operate in the natural space environment. Based on discussions with ISS thermal environment engineers [18] and a review of applicable documentation [15,17,19], it is likely that at a minimum the following environmental hardening measures will need to be implemented: (1) a heat dissipation system to be used while the system is operational; (2) a heating system (active or passive) to be used when the system is non-operational; and (3) metallic shielding of electronic equipment to mitigate the effects of ionizing radiation (this could also be used for EMI shielding purposes). The specifics and exact extent of the hardening measures required need to be determined based on the results of a detailed environmental analysis. An analysis of this type was beyond the scope of the initial concept study, but should be performed as part of the implementation program.

If the costs of locating the measurement package outside the ISS are determined to be prohibitive, then a fall-back option of re-packaging the measurement hardware inside the ISS as an EXPRESS rack payload is a viable alternative. Most COTS measurement hardware should be able to meet the ISS internal payload atmospheric requirements [20]. Also, ionizing radiation, atomic oxygen, and ionospheric plasma effects should be less severe inside the ISS. The 20 inch diameter, nadir-facing window in the ISS U.S. laboratory would permit the incident electromagnetic fields to be sampled. Because of the coupling and cavity effects resulting from the internal location of the antennas, it is recommended that a custom-designed, anechoically-lined hood be placed over the antennas (with the hood opening placed against the nadir window). This anechoically-lined hood can significantly increase the total weight of the EFMP (particularly if ferrite tile absorber is used). Also, the lower frequency range of 100 MHz would likely have to be increased by a factor of 2 to 4 to improve the: (1) coupling of incident fields through the 20 inch diameter window aperture and (2) field absorption from the anechoic material. The antennas can be calibrated over the applicable frequency range using the hooded antennas with a simulated 20 inch mounting configuration.

6. INTERFACE REQUIREMENTS DEFINITION

The objective of this task was to define the International Space Station (ISS) interface requirements that are most relevant to the EFMP concept development. It is GTRI's judgement that requirements related to package size limits, package weight limits, electrical power capacity, and data interface accommodations will have the most impact (relative to other interface requirements) on the initial concept development. Thus, determining these requirements for both external and internal payloads were the focus of this task.

The pertinent references [3,4] were reviewed to determine the interface requirements for external payloads. The EXPRESS program has been implemented by NASA to standardize the accommodations and interface requirements (data, power, structural, and mechanical) for externally mounted ISS payloads. The EXPRESS Pallet System (ExPS) will be the primary vehicle for integrating attached external payloads to the (ISS). NASA personnel have indicated that any externally located EFMP components will be implemented using the ExPS. It should be noted that the development specification is currently in draft form and not all requirements are finalized. The following external payload interface requirements were determined:

(1) Maximum Payload Weight = 500 lbs

(2) Maximum Dimensions: Length = 46 in., Width = 34 in., Height = 49 in.

(3) Maximum Volume = 44.2 Cu. Ft.

(4) Power Feed Voltage: 120 Vdc and 28 Vdc (2 feeds for each)

(5) Available Power (per payload): 2500 watts max at 120 Vdc, 500 watts max at 28 Vdc

(6) Available Data Links: IEEE 802.3 Ethernet 10BASE-T and MIL-STD-1553B

The EXPRESS Rack Payloads Interface Definition Document (IDD) [15] was reviewed to determine the internal payload requirements. This IDD defines and controls the design of the interfaces between the EXPRESS Rack facility and the payloads using the accommodations of the EXPRESS Rack, as well as, the EXPRESS Transportation Rack (used for orbiter launch/landing transportation to the ISS). GTRI reviewed the IDD and other pertinent documentation [17] to ascertain the interface requirements that are most relevant to the EFMP concept development. A payload that utilizes the equivalent volume of two single payloads (two standard module lockers) is considered a standard payload under the IDD. The payload does not have to be mounted in the standard module lockers, but can provide its own unique support structure. Also, non-standard payloads can be mounted in the EXPRESS Rack with appropriate coordination through the payload integrator. These non-standard payloads can include non-standard data or signal interfaces. This provision could be used to allow for an RF connection between the spectrum analyzer (mounted in the EXPRESS Rack) and the antennas located at the Nadir window. This provision could also would allow for an IEEE-488 or RS-232 link from the spectrum analyzer to a laptop computer located external to the rack. In addition, there will be laptop computers on the ISS dedicated for EXPRESS Rack payload use. It may be possible to use these computers to control the electric field measurement system, rather than supplying a laptop computer as part of the measurement package. In general, the IDD appears to allow for quite a lot of flexibility for the design of payload packages. However, standard payload interface requirements for EXPRESS Rack installation (for a double payload) are as follows:

(1) Maximum Payload Weight: 140 lbs

(2) Maximum Dimensions: Length = 20 in., Width = 17 in., Height = 20 in.

(3) Maximum Volume: Approximately 4 cu. ft.

(4) Power Feed Voltage: 28 Vdc

(5) Available Power: 1120 watts max at 28 Vdc, 40 amps

(6) Available Data Links: IEEE 802.3 Ethernet 10BASE-T and RS-422

7. QUALIFICATION REQUIREMENTS DEFINITION

Environmental factors that must be considered when operating outside the ISS include: (1) thermal; (2) structural loading and vibration; (3) on-orbit plasma environment; (4) ultraviolet radiation exposure; (5) pressure; (6) atomic oxygen exposure; (7) humidity; (8) ionizing radiation; and (9) electromagnetic interference (EMI). Since the measurement package is being developed using COTS equipment, it is expected that a thorough environmental analysis and test program would have to be undertaken and environmental conditioning measures implemented as necessary to ensure survival of the hardware in a space environment.

The expected ambient temperature range for a nadir viewing EXPRESS Pallet payload is -120° F to 140° F [18]. Acceptable temperature ranges for all the measurement package COTS hardware has not been identified at this time; however, typical operating temperatures for COTS spectrum analyzers are 32° F to 130° F and storage temperatures typically range from -40° F to 165° F. Also, it should be noted, that the additional heat generated during operation of the system will likely shift the payload ambient temperature range higher. Thus, it is probable that a payload heat dissipation system will be required during operation of the measurement package and a heating system will be required when the system is non-operational. One of the primary goals of the environmental analysis, to be conducted prior to testing, will be to determine the specific payload thermal conditioning measures that must be implemented to allow the measurement package to function in the on-orbit space environment.

The most severe structural loading and vibration stresses to the EFMP will occur during the lift-off phase of the payload deployment. These stresses greatly exceed the on-orbit stresses (during operation on the ISS) and will be the driver for structural loading and vibration qualification. The launch loading and vibration effects will depend on where the payload is located in the shuttle (Middeck Locker, Mini-Pressurized Logistics Module, etc.). Worst-case load factors for lift-off can be as high as 11.0 g's [14]. Payloads must be designed to maintain positive margins of safety during lift-off. If the measurement package is designed to be returned to Earth in operational condition, load design requirements are even higher (for landing and emergency landing qualification). Guidance for evaluating lift-off loads is provided in Reference 20. The measurement package also must be qualified to a vibration environment over the frequency range of 20 to 2000 Hz. Worst-case levels for this environment consist of an acceleration power spectral density of 0.04 g^2/Hz and a composite acceleration of 6.5 g_{rms}. In addition the measurement package payload must be designed to have a first mode fundamental frequency greater than or equal to 35 Hz.

The measurement package payload should be tested and qualified to survive in the same neutral atmosphere environment as specified for the EXPRESS Pallet System [19]. The relevant requirements for this environment are as follows: (1) the system must meet performance requirements in on-orbit plasma environment of +40 volts; (2) the system must meet performance requirements during ultraviolet radiation exposure of 118 W/m^2 for wavelengths less than 0.4 µm; (3) the system must meet performance requirements during exposure to a minimum pressure of $5.5A10^{-12}$ psia; (4) the system must operate and meet performance requirements following exposure to a maximum pressure rate change of –0.76 psi per second over a pressure range of 15.2 to $1.94A10^{-9}$ psia; (5) the system must meet performance requirements during exposure to atomic oxygen levels of $5.0A10^{21}$ atoms/cm^2/year; and (6) the system must be capable of operating and meet performance requirements in an environment of 0% to 100% humidity.

Ionizing radiation consists primarily of high energy charged particles (protons, electrons, and heavy ions) that are produced by several sources including magnetosphere processes, cosmic rays, and solar flares. Effects to electronic equipment are classified as Total Ionizing Dose (TID) effects and Single Event Effects (SEE). SEEs occur as the result of a single ionizing particle interacting with electronic components. Generally, TIDs and SEEs are estimated as a function of the thickness of the aluminum shielding that is present around the equipment. During the payload development program, the ionizing radiation design environment for the ISS [21] should be used to perform a detailed TID and SEE evaluation as part of the overall environmental analysis. In addition, recommended test levels for SEEs are specified in Reference 22. As was mentioned previously, it is anticipated that shielding measures will have to be implemented for the COTS equipment to survive in the natural space environment. Specific shielding measures will be determine based on the results of the pre-test analysis.

The measurement package must demonstrate compliance with the conducted and radiated emissions requirements [1]. Also, conducted and radiated susceptibility testing should be performed on the measurement package. The radiated susceptibility testing should be performed with the antennas removed and the RF input to the spectrum analyzer terminated with a 50 Ω load. Normally, non-safety critical payloads are tested to the RS03PL limit which ranges from 5 V/m to 60 V/m over a 14 kHz to 15.2 GHz frequency range. However, because the measurement package must be able to measure field levels up to 250 V/m, radiated susceptibility testing should be performed at 250 V/m or at the highest test level that can be generated (possibility only 200 V/m at commercial test houses). Equipment aluminum shielding that is implemented to protect against ionizing radiation effects can also serve to harden the equipment against EMI effects provided that care is taken to treat all enclosure apertures and penetrations (gasketing, filtering, etc.).

The pre-test environmental analysis will be based on the expected operational environment described above. The objective of the analysis will be to determine the final mechanical and structural design for the payload package that will allow the measurement system to operate in the external space environment. After the prototype payload package has been fabricated, it will under go complete environmental testing to verify its qualification to the expected operational environment.

8. PREFERRED MEASUREMENT PACKAGE CONCEPT SELECTION

This task primarily consisted of evaluating the advantages and disadvantages of internal versus external location of the measurement package. The recommended EFMP concept was developed based on the NASA defined objectives for the system. Fundamental design issues for the measurement package included: (1) determining the required frequency resolution; (2) the availability and usefulness of using COTS equipment to implement the system; (3) evaluating the trade-offs between an externally versus internally located system; and (4) identifying a design that meets the desired performance specifications. It is NASA's desire to use COTS equipment and to collect data in reasonably narrow frequency bands (bandwidths of a few MHz). Thus, the recommended measurement package has been designed using COTS equipment and is built around a scanning superheterodyne receiver (spectrum analyzer) which will allow a nominal frequency resolution of 3 MHz. GTRI recommends that the measurement package be located externally to the ISS as a nadir-facing EXPRESS pallet payload. A detailed description of the measurement configuration and the procedures for collecting the electric field measurement data are provided in the Implementation Plan.

9. IMPLEMENTATION PLAN PREPARATION

The Implementation Plan is provided in Appendix C. This Plan is intended to serve the purpose of risk mitigation and can be used as a program-planning guide for implementing the ISS EFMP flight experiment. The Implementation Plan includes: (1) a specific description of required experiment hardware; (2) experiment set-up and start-up procedures including a pictorial depiction of the experiment; (3) proposed interface requirements specific to the experiment; (4) a description of the on-ground testing needed for proof-of-concept; and (5) an analysis of the number of orbits required to get reliable measurement data.

Note that the Implementation Plan is formatted so that it can be used as a stand-alone document. Therefore, it contains its own table-of-contents as well as its own numbering scheme for tables and figures. For completeness, some of the material documented in the body of this report is repeated in the Implementation Plan.

10. REFERENCES

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[22] "Space Station Ionizing Radiation Effects Test and Analysis Techniques," NASA Document SSP 30513, 26 September 1994.

APPENDIX A

MATHCAD® MODEL USED TO CALCULATE ANTENNA FACTOR REQUIREMENTS

Mathcad® Model Used to Calculate Antenna Factor Requirements

This appendix contains a Mathcad® model which was developed to calculate the maximum allowable AF (and, equivalently, the minimum required antenna gain) to meet the measurement sensitivity requirements of the EFMP. The user provides the following inputs to the model: the frequency range and the number of points to be used for the calculations; the total amount of RF attenuation (both internal and external); the receiver IF bandwidth and noise figure; the antenna temperature; the minimum acceptable signal-to-noise ratio (S/N); the desired minimum electric field sensitivity; and the coaxial cable parameters (length, geometry, dielectric constant and power factor, and conductor material parameters). The program first calculates the attenuation of the coaxial transmission line and then plots the results as a function of frequency. Next, the program calculates the minimum gain and maximum antenna factor to achieve the sensitivity requirements. Finally, the program plots both the minimum antenna gain and the maximum antenna factor as a function of frequency.

For the sample calculations shown in this appendix, the antenna and the receiver are assumed to be connected with ten feet of RG-55 coaxial cable. (Note that RG-55 was selected for these sample calculations because parametric data was readily available for input to the model and measured insertion loss data was available to validate the insertion loss calculations. However, low loss, microwave coaxial cable should be used in the actual design to improve the measurement sensitivity.) The receiver noise figure is based on the measured values for an HP8566B spectrum analyzer. A 3 MHz resolution bandwidth and no additional RF attenuation are assumed. The antenna temperature is assumed to be 300 °K. The desired electric field sensitivity is chosen to be 2 V/m and the minimum signal-to-noise ratio is selected to be 10 dB.

Calculation of Minimum Antenna Gain / Maximum Antenna Factor Requirements

Specify the Range of Frequencies Over Which Calculation Will be Performed:

$fmin := 100 \cdot 10^6$ $\quad$ $fmax := 18 \cdot 10^9$

Specify Number of Points Per Decade and Determine Frequencies:

$ppd := 1000$ $\quad$ $N := (\log(fmax) - \log(fmin)) \cdot ppd + 1$ $\quad$ $kf := 0..N-1$ $\quad$ $f_{kf} := fmin \cdot 10^{\frac{kf}{ppd}}$ $\quad$ $N = 2.256 \cdot 10^3$

$\lambda_{kf} := \dfrac{2.998 \cdot 10^8}{f_{kf}}$ $\quad$ $fmhz_{kf} := \dfrac{f_{kf}}{10^6}$

Specify Total Amount of RF Attenuation (both external and internal):

$RFATTN := 0$ dB

Specify Receiver IF Bandwidth (in Hz) and NF (in dB): $BWIF := 3 \cdot 10^6$

$$NF_{kf} := \begin{cases} 34 & \text{if } f_{kf} < 5.8 \cdot 10^9 \\ 41 & \text{if } 5.8 \cdot 10^9 \le f_{kf} < 12.5 \cdot 10^9 \\ 46 & \text{otherwise} \end{cases}$$

Specify Antenna Temperature (in deg K): $To := 300$

Specify Minimum Signal-to-Noise Ratio (in dB): $SNRmin := 10$

Specify Minimum Electric Field Sensitivity (in V/m): $Emin := 2$

Specify Coaxial Cable Parameters:

Specify Coaxial Cable Length (in feet): $lengthinfeet := 10$

Specify Coaxial Cable Geometry (in inches):

$d1inRG55 := 0.035$ $\quad$ $d2inRG55 := 0.116$

Specify Dielectric Constant and Power Factor:

$\varepsilon rRG55 := 2.23$ $\quad$ $PFRG55 := .0008$ $\quad$ $\varepsilon o := 8.854 \cdot 10^{-12}$ $\quad$ $\varepsilon RG55 := \varepsilon rRG55 \cdot \varepsilon o$

Calculate Characteristic Impedance:

$$\mu o := 4 \cdot \pi \cdot 10^{-7} \qquad ZcRG55 := \sqrt{\frac{\mu o}{\varepsilon rRG55 \cdot \varepsilon o}} \cdot \frac{\ln\left(\frac{d2inRG55}{d1inRG55}\right)}{2 \cdot \pi} \qquad ZcRG55 = 48.111$$

Specify Center Conductor Material Parameters:

$\sigma Cu := 5.8 \cdot 10^7$ $\quad$ $\rho Cu := \dfrac{1}{\sigma Cu}$ $\quad$ $\rho r1RG55 := 0.95$ $\quad$ $\mu r1RG55 := 1$ $\quad$ $\rho 1RG55 := \rho r1RG55 \cdot \rho Cu$ $\quad$ $\mu 1RG55 := \mu r1RG55 \cdot \mu o$

Specify Shield Material Parameters:

$\rho r2RG55 := 0.95 \quad \mu r2RG55 := 1 \quad \rho 2RG55 := \rho r2RG55 \cdot \rho Cu \quad \mu r2 := 1 \quad \mu 2RG55 := \mu r2 \cdot \mu o$

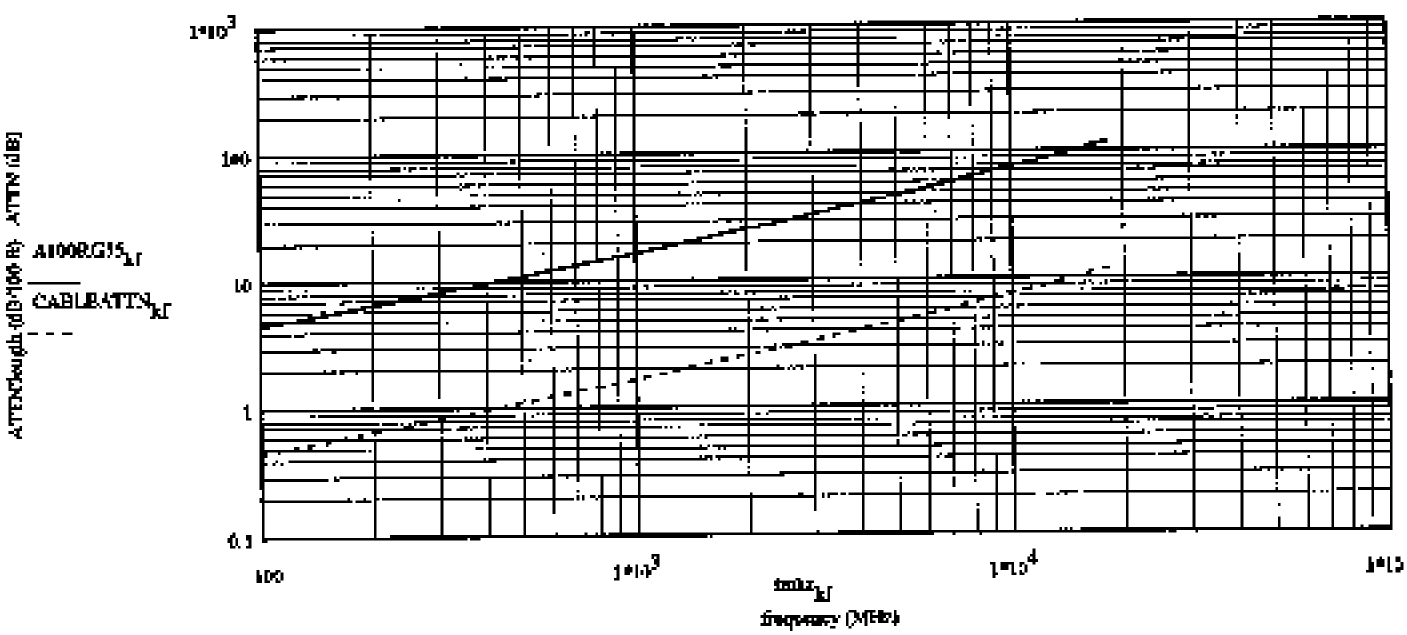
Calculate the Total Transmission Line Resistance per 100 Feet:

$$RtRG55_{kf} := 0.125 \cdot \left(\frac{1}{d1inRG55} \sqrt{\mu r1RG55 \cdot \rho r1RG55} + \frac{1}{d2inRG55} \sqrt{\mu r2RG55 \cdot \rho r2RG55} \right) \cdot \sqrt{fmhz_{kf}}$$

(Note: coefficient was increased from 0.1 to 0.125 to match published data.)

Calculate the Per Unit Length Attenuation (dB/100ft) and Total Attenuation (dB) of Coaxial Line:

$$A100RG55_{kf} := 4.34 \frac{RtRG55_{kf}}{ZcRG55} + 2.78 \cdot fmhz_{kf} \cdot \sqrt{\epsilon rRG55} \cdot PFRG55 \quad CABLEATTN_{kf} := A100RG55_{kf} \cdot \left(\frac{lengthinfeet}{100} \right)$$



Calculate Minimum Gain (Maximum Antenna Factor) to Achieve Sensitivity Requirements:

$To := 298 \qquad F_{kf} := 10^{\frac{NF_{kf}}{10}} \qquad Tr_{kf} := To \cdot (F_{kf} - 1) \qquad k := 1.38 \cdot 10^{-23}$

$h := 6.63 \cdot 10^{-34} \qquad Ts_{kf} := Ta + Tr_{kf} \qquad Nif_{kf} := k \cdot Ts_{kf} \cdot BWIF \qquad NifdB_{kf} := 10 \cdot \log(Nif_{kf})$

$$Gmin_{kf} := SNRmin + RFATTN + NifdB_{kf} + 10 \cdot \log(377 \cdot 4 \cdot \pi) + A100RG55_{kf} \cdot \frac{lengthinfeet}{100} - 20 \cdot \log(\lambda_{kf}) - 20 \cdot \log(Emin)$$

$$AFmax_{kf} := \left[10 \cdot \log\left[\frac{377 \cdot 4 \cdot \pi}{50 \cdot (3 \cdot 10^8)^2} \right] + 20 \cdot \log(f_{kf}) \right] - Gmin_{kf}$$

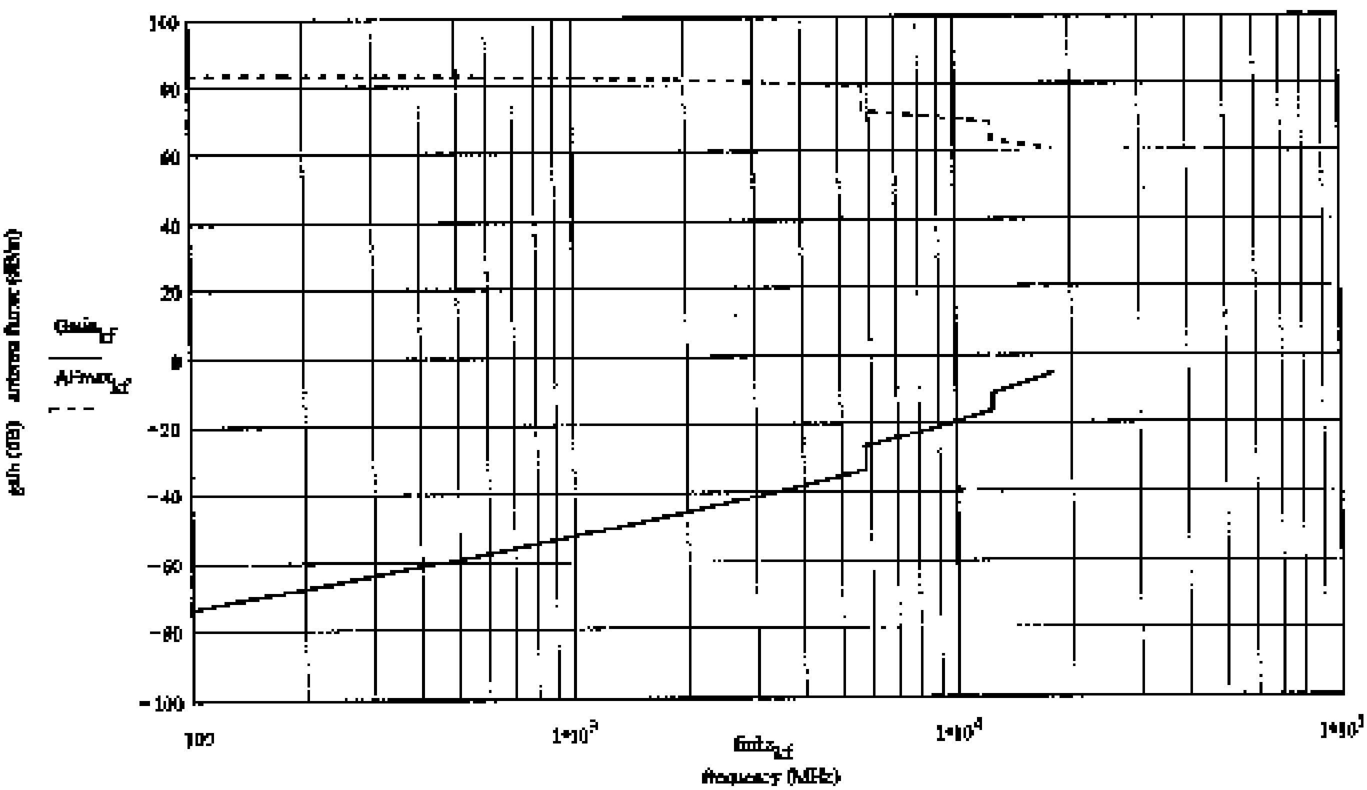


Figure 1. Gain and AF vs. Frequency

APPENDIX B

MATHCAD^{â} MODELS USED TO CALCULATE MEASUREMENT TIME REQUIRED TO ACHIEVE A DESIRED PROBABILITY-OF-INTERCEPT

Mathcadâ Models Used to Calculate Measurement Time Required to Achieve a Desired Probability-of-Intercept

This appendix contains Mathcad® models that were developed to calculate the measurement time required to achieve a desired probability-of-intercept (POI) for the EFMP. Two different algorithms were used for calculating the POI for a scanning receiver [C-1, C-2]. Both algorithms are based on the use of independent and periodic window functions. The first window function is used to represent the pulsed signal from the emitter of interest. The width of this function corresponds to the pulse width and the period of this window corresponds to the pulse repetition interval (PRI). The second window function is used to represent the frequency scan of the receiver. The width of this window is the time it takes for the spectrum analyzer bandpass to "sweep by" a fixed frequency of interest (given by the ratio of the resolution bandwidth and the sweep rate). The period of this second window is simply the total scan time (ST). The POI for a given measurement or observation time is calculated based on the probability of these two window functions overlapping. Conversely, given a desired POI, the measurement or observation time required to achieve this POI can also be calculated.

The Mathcad® models in this appendix calculate and plot the measurement or observation time required to achieve a desired POI. Since References C-1 and C-2 provide different algorithms and the results can disagree radically under certain conditions, both algorithms are used and compared. As can be seen in the final plot, except for very high POIs, the differences in predicted observation times are extremely small for typical EFMP measurement conditions. It appears that the Hatcher [C-1] equations may be in slight error and thus the Self [C-2] equations are recommended for use in further, more detailed analyses.

These model is based on three basic assumptions. The first assumption is that the ISS is being tracked by the radar-of-interest. Otherwise, a third window function (i.e., the window function associated with the scanning radar) would have to be added to the calculations and the POIs would be extremely low for reasonable observation times. The second assumption is that a "fast scan" receiver frequency scanning method is used. This "fast scan" approach uses the "MAX HOLD" feature of the spectrum analyzer to display the maximum detected amplitudes from a number of sweeps using a relatively fast sweep rate before storing the trace. With this approach, radar pulses could be missed if the ST is a harmonic or a sub-harmonic of the radar PRI and, thus, a third assumption is made that this condition is avoided. (These harmonically related scan conditions can be avoided by carefully selecting the STs and/or by using different STs on alternate scans to insure a high POI.) Note that by definition an intercept becomes a detection only if the intercepted signal strength exceeds the detection threshold sensitivity of the receiving system.

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[C-2] Self, A. G., "Intercept Time and Its Prediction," Journal of Electronic Defense, August 1983, pp. 49-55.

Calculation of Probability of Intercept (ala Hatcher)

Specify the Range of Probability of Intercept Over Which Calculation Will be Performed:

$Pimin := 1 \cdot 10^{-2}$ $\qquad$ $Pimax := 9.95 \cdot 10^{-1}$

Specify Number of Points Per Decade and Determine Frequencies:

$ppd := 1000$ $\qquad$ $N := (\log(Pimax) - \log(Pimin)) \cdot ppd + 1$ $\qquad$ $kp := 0 .. N - 1$ $\qquad$ $Pi_{kp} := Pimin \cdot 10^{\frac{kp}{ppd}}$ $\qquad$ $N = 1.999 \cdot 10^{3}$

Specify Spectrum Analyzer Resolution Bandwidth (in Hz), Scan Range (in Hz), and Scan Time (in sec):

$RBW := 3 \cdot 10^{6}$ $\qquad$ $SR := 16 \cdot 10^{9}$ $\qquad$ $ST := 0.4$

Specify Signal Pulse Width (in sec) and Pulse Repetition Interval (in sec):

$\tau := 1 \cdot 10^{-4}$ $\qquad$ $PRI := 1 \cdot 10^{-2}$

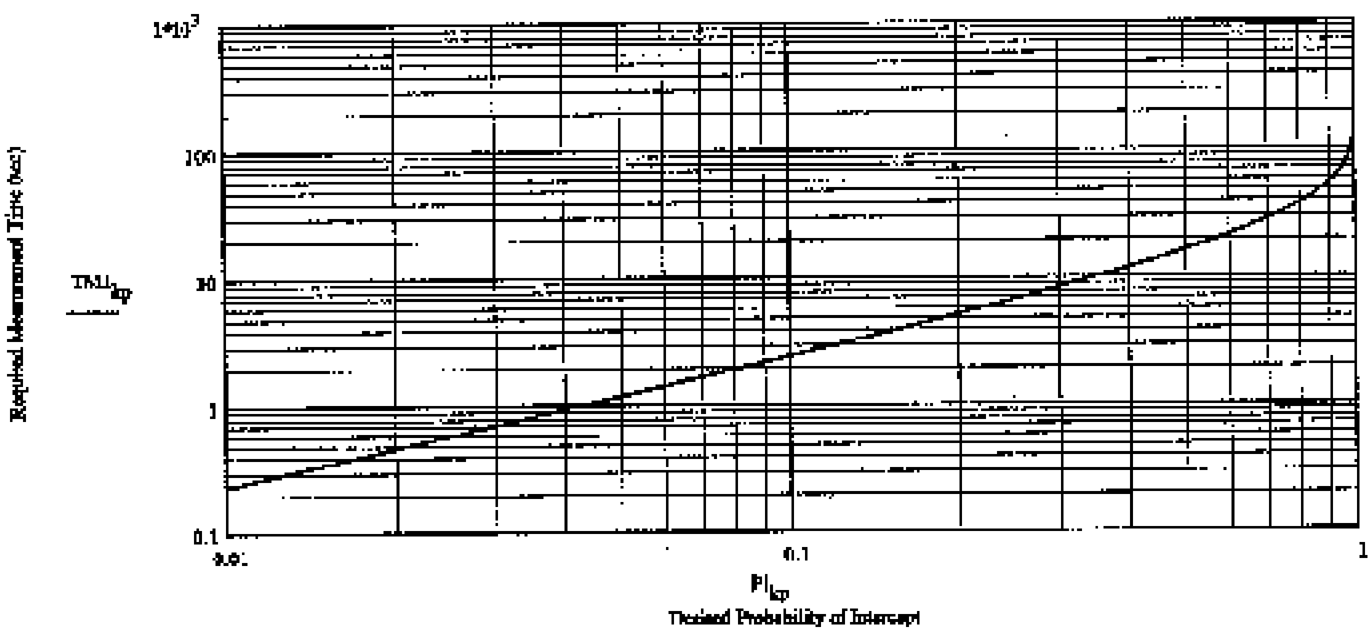
Calculate Probability of Intercept After One PRI:

$$P1 := \frac{\left[\tau + \frac{(RBW \cdot ST)}{SR} \cdot \left[1 - \frac{(RBW \cdot ST)}{2 \cdot SR \cdot PRI}\right]\right]}{ST}$$

(ST>PRI, ST-PRI>τ, PRI>(RBW*ST/SR))

Calculate Required Measurement Time as a Function of Desired Probability of Intercept:

$$TM_{kp} := PRI \cdot \frac{\log(1 - Pi_{kp})}{\log(1 - P1)}$$



Calculation of Probability of Intercept (sig Self)

Calculate the Mean Period of Simultaneous Overlaps:

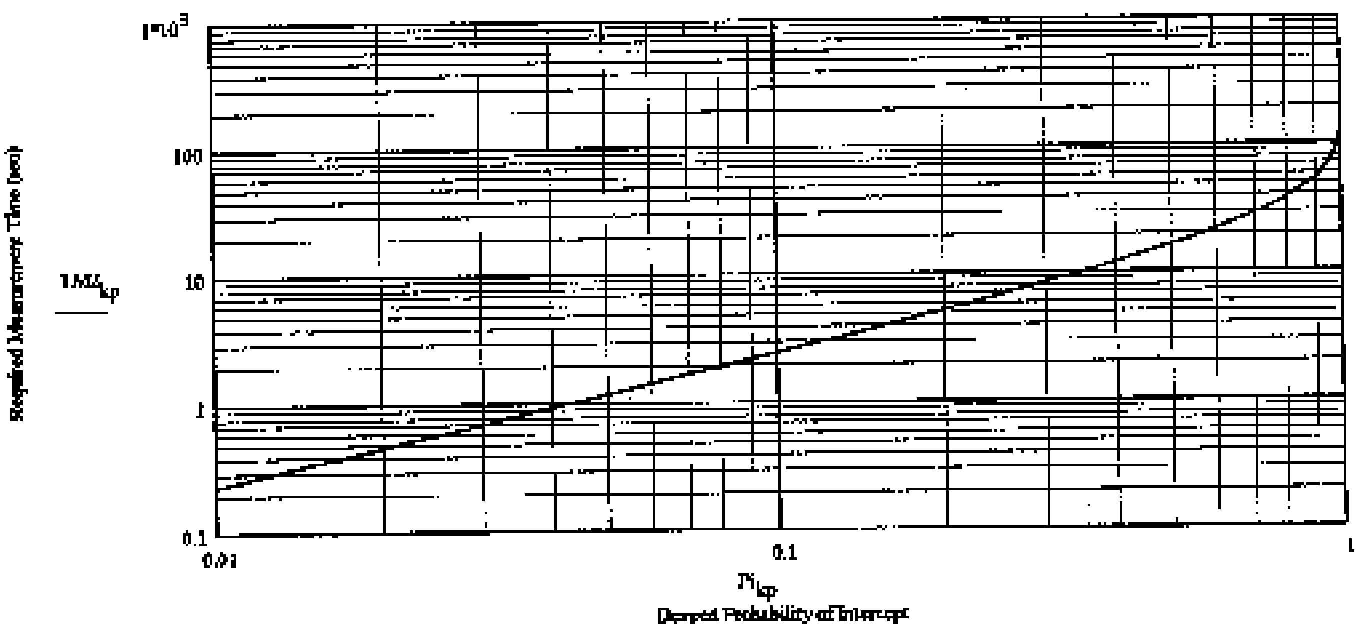
$$To := \frac{PRI \cdot SR \cdot ST}{\tau \cdot SR + RBW \cdot ST} \qquad To = 22.857$$

Calculate Required Measurement Time as a Function of Desired Probability of Intercept:

$$Po := \frac{\tau \cdot RBW}{PRI \cdot SR} \qquad K := 1 - Po \qquad Po = 1.875 \cdot 10^{-6}$$

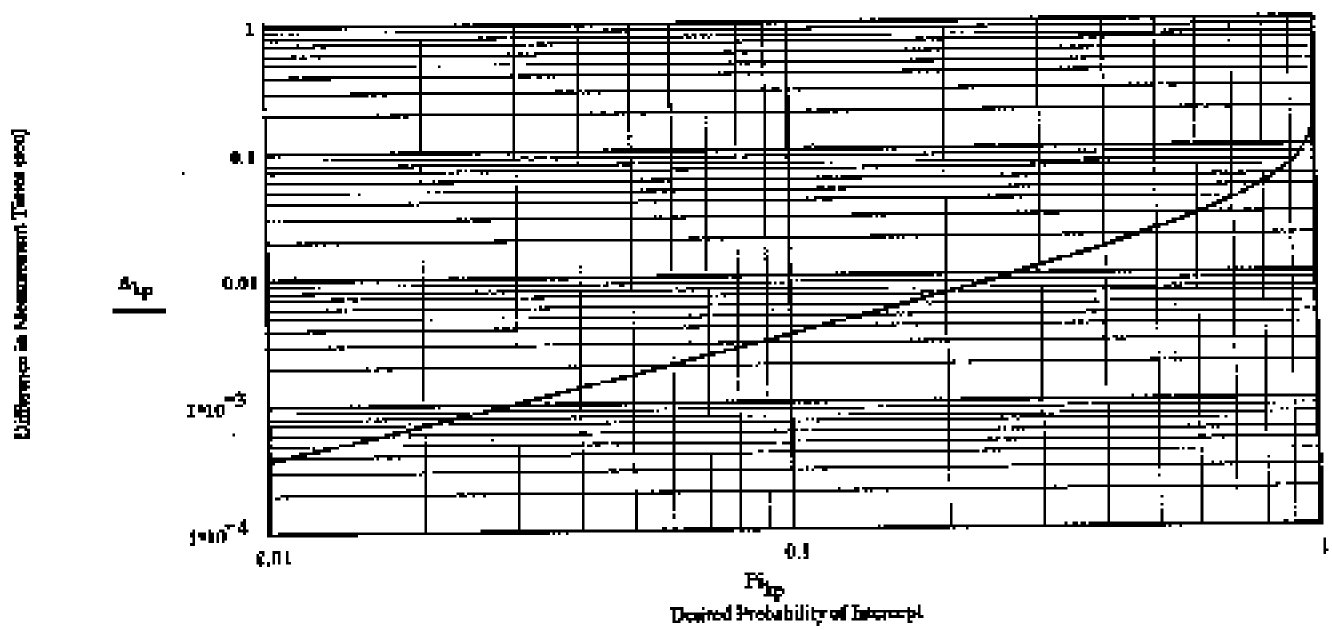
$$TM2_{kp} := -To \cdot \ln\left(\frac{1 - Pi_{kp}}{K}\right)$$

Note: Must scan $-To \cdot \ln(.5) = 15.843$ seconds to achieve a POI of 50%.



Calculate the Difference Between the Hatcher and Self Measurement Time Algorithms:

$\Delta_{kp} := TM1_{kp} - TM2_{kp}$



APPENDIX C – IMPLEMENTATION PLAN

INTERNATIONAL SPACE STATION
ELECTRIC FIELD MEASUREMENT PACKAGE
IMPLEMENTATION PLAN

Contract No. H-28501D

20 January 1998

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1. INTRODUCTION

1.1 Scope and Objective

The purpose of this document is to provide an implementation plan for an Electric Field Measurement Package (EFMP) to be flown on the International Space Station (ISS). The primary objective of this plan is to provide initial concept information required for fielding an EFMP that can: (1) accurately measure the on-orbit electric field environment across the applicable frequency range of significant ground and ISS transmitters; (2) supply data and data analyses to NASA to be published for use by payload developers; (3) be compatible with ISS interface requirements; and (4) meet the applicable ISS qualification requirements. It should be noted that this implementation plan has been developed based on an initial concept study only, and is not intended to provide all the engineering details necessary for final implementation of the measurement package and experimental procedures.

The scope of this document includes: (1) a description of required performance specifications; (2) a definition of the ISS interface requirements; (3) a recommended measurement package concept; (4) a description of the required package hardware; (5) a description of proof-of-concept testing; (6) a description of experimental procedures; and (4) an analysis of the measurement time (number of orbits) required to get reliable data.

2. PERFORMANCE SPECIFICATIONS

One of the initial tasks of the concept study was to define the desired basic performance specifications for the EFMP. Over the course of the program, the specifications changed and evolved somewhat as design possibilities were considered and evaluated. The final performance specifications for the measurement package are defined as follows:

(1) Frequency Range (minimum) = 100 MHz to 18 GHz,
(2) Sensitivity (minimum) = 2 V/m,
(3) Dynamic Range (minimum) = 42 dB,
(4) Far-Field Antenna Factor = 31 to 70 dB/m,
(5) Frequency Resolution (typical resolution bandwidth) = 3 MHz,
(6) E-Field Sampling Rate (minimum) = 8 millihertz, and
(7) Data Sampling Rate (minimum) = 8 millihertz.

The frequency range specification of 100 MHz to 18 GHz was chosen since most of the significant transmitters of interest operate in this range [1,2]. The measurement package will detect both on-board and ground based transmitters; however, detection of the ground based transmitters was given higher priority for the system. In particular, NASA is interested in measuring the field levels produced by the UHF and C-band radars that comprise the U. S. Space Surveillance Network (SSN). The lower frequency limit specification of 100 MHz is desired to detect Russian space surveillance radars, many of which operate in the VHF band. The corresponding design trade-off for operation at 100 MHz is the large physical size of the antennas that are required at this frequency. This large antenna size greatly pushes the measurement package size constraints. The upper frequency limit of 18 GHz allows for coverage all emitters of interest in the NASA Contractor Report 4776 [1] except the 35 and 95.5 GHz instrumentation radars located at Roi-Namur in the Marshall Islands The 18 GHz upper frequency limit was chosen because: (1) very few electromagnetic interference (EMI) problems are caused by millimeter wave emitters due to the high susceptibility thresholds of electronic devices and the small coupling cross-sections of receptors at these very short wavelengths; and (2) a measurement package design that included frequency bands above 18 GHz would be cost prohibitive when compared with the limited additional data that would be collected at these bands.

The 2 V/m system sensitivity level is considered an adequate lower limit for detecting field levels that will be of interest. Currently, all ISS payloads must meet a minimum radiated susceptibility test requirement of 5 V/m [3]. Thus, the possibility of field levels below 2 V/m producing significant EMI effects to on-orbit equipment is not considered likely. The 42 dB dynamic range specification will permit accurate measurement of field levels up to 250 V/m which approximates the highest predicted on-orbit field level (due to ground emitters) for the ISS [1].

As mentioned previously, measurement of significant ground based emitters (and SSN radars in particular) will be the highest priority for the measurement package. The majority of these ground based emitters are pulsed radars. The spectrum analyzer based measurement package detailed in this report will have the capability to accurately measure the peak field levels of the majority of radars of interest. Based on a review of the signal characteristics of the radars of interest, specifications for the measurement system's "default mode" of data collection were chosen to allow for optimum measurement of these peak field levels. It is envisioned that this default mode will be the data collection mode used for routine field level monitoring. For the default mode, the resolution bandwidth of the spectrum analyzer was chosen to be 3 MHz. This will allow the peak field level to be accurately measured for all radars with a pulsewidth greater than 0.33 :s. The E-field sampling sweep rate over the complete band (100 MHz to 18 GHz) was chosen to be 8 millihertz. This rate ensures that all radars with pulse repetition frequencies greater than 100 Hz will be detected (assuming the signal level exceeds the measurement system's sensitivity level) during a default mode scan. The data storage time will be small compared to the frequency scan time. Thus, the data sampling rate (collection of one complete set of data over the entire 17.9 GHz range) is also 8 millihertz.

3. ISS PAYLOAD INTERFACE REQUIREMENTS

Payloads on the ISS can be implemented either externally or internally to the space station structure. NASA has implemented the EXpedite the Process of Experiments to Space Station (EXPRESS) program to standardize the accommodations and interface requirements for externally mounted ISS payloads. The EXPRESS Pallet System (ExPS) will be the primary vehicle for integrating attached external payloads to the ISS and the EFMP hardware components will have to be compatible with the ExPS interface requirements. The interface requirements for an individual payload are defined as follows [4]:

(1) Maximum Payload Weight = 500 lbs,
(2) Maximum Dimensions: Length = 46 in., Width = 34 in., Height = 49 in.,
(3) Maximum Volume = 44.2 Cu. ft.
(4) Power Feed Voltage: 120 Vdc and 28 Vdc (2 feeds for each),
(5) Available Power: 2500 watts max at 120 Vdc, 500 watts max at 28 Vdc, and
(6) Available Data Links: IEEE 802.3 Ethernet 10BASE-T and MIL-STD-1553B.

An internal EXPRESS Rack facility is provided to house payloads that will be located inside the ISS U. S. Laboratory. This EXPRESS Rack accommodations are integrated into the International Standard Payload Rack (ISPR) structure. The EXPRESS Rack facility consists of mounting provisions defined as the Middeck Locker (MDL) locations and the Standard Interface Rack (SIR) drawer locations. Various payload mounting provisions are provided as part of the EXPRESS Rack facility. However, a payload does not have to use the standard provisions and a unique support structure can be provided by the payload developer. A payload that utilizes the equivalent volume of two single payloads is considered a standard payload under the EXPRESS Rack facility. Also, non-standard payloads can be mounted in the EXPRESS Rack with appropriate coordination through the NASA payload integrator. These non-standard payloads can include non-standard data or signal interfaces. In general, the EXPRESS Rack facility allows for considerable flexibility in the design of payload packages. The standard payload interface requirements for a double EXPRESS Rack MDL location installation (equivalent volume of two single payload locations) are as follows [5,6]:

(1) Maximum Payload Weight: 140 lbs,
(2) Maximum Dimensions: Length = 20 in., Width = 17 in., Height = 20 in.,
(3) Maximum Volume: Approximately 4 cu. ft.,
(4) Power Feed Voltage: 28 Vdc,
(5) Available Power: 1120 watts max at 28 Vdc, and
(6) Available Data Links: IEEE 802.3 Ethernet 10BASE-T and RS-422.

4. RECOMMENDED MEASUREMENT PACKAGE CONCEPT

4.1 General Concept Development Issues

The recommended EFMP concept is based on the NASA defined objectives for the system. Fundamental design issues for the measurement package included: (1) determining the required frequency resolution; (2) determining the feasibility of using commercial-off-the-shelf (COTS) equipment to implement the system; (3) evaluating the trade-offs between an externally versus an internally located system; and (4) identifying a design that meets the desired performance specifications. It is NASA's desire to use COTS equipment and to collect data in reasonably narrow frequency bands (bandwidths of a few MHz). Thus, the measurement package recommended in this document has been designed using COTS equipment and is built around a scanning superheterodyne spectrum analyzer which will allow a frequency resolution of 3 MHz (when operated in the proposed default mode).

In the original concept (proposed early in the study program), the measurement package antennas were placed external to the ISS (as part of a nadir-facing payload package) and the electronic components of the system were placed inside to the ISS. The antennas were to be connected to an internal spectrum analyzer via an RF cable. This configuration was considered optimum as the accuracy of the measured field levels would not be affected by the coupling and cavity effects induced by the antennas being located inside the U. S. Laboratory (and pointed through a 20 inch diameter nadir-facing window). In addition, only the antennas and RF cabling would have to be qualified to the harsh natural space environment. However, based on a review of the EXPRESS Pallet System for external payloads there appears to be no practical method for implementing this type of configuration because the external EXPRESS System has no provision for an analog RF link. Therefore, the only two viable options for location of the measurement package are to either: (1) package the entire system as an external EXPRESS pallet payload and to collect data via the data links provided by the EXPRESS system; or (2) locate the entire system internally to the ISS and package the experiment as a Nadir window facing experiment (antennas pointing through the Nadir window).

It is recommended that the measurement package be located externally to the ISS as a nadir-facing EXPRESS pallet payload. With this measurement configuration the drivers of the system equipment package design are: (1) the size constraints afforded by the EXPRESS pallet payload envelope; and (2) the environmental hardening measures that have to be implemented to ensure the survival of the COTS equipment in the natural space environment. The full extent of the hardening measures that will be required will not be determined until the system has undergone environmental analyses and testing (as part of the proof-of-concept testing phase of implementation). If it is determined that the required environmental hardening measures are too costly or not feasible; then a fall back option of re-packaging the measurement hardware as an EXPRESS rack payload (with the antennas located at the U. S. Lab nadir-facing window) could be considered. Because of the coupling and cavity effects resulting from the internal location of the antennas, it is recommended that a custom-designed, anechoically-lined hood be placed over the antennas (with the hood opening placed against the nadir window). The lower frequency of 100 MHz would likely have to be increased by a factor of 2 to 4 to accommodate the 20 inch aperture. The antennas can be calibrated over the applicable frequency range using a simulated 20 inch mounting configuration. Also, it should be noted that the hood would have to be lined with dense ferrite absorbing materials which will likely result in the hood weight becoming a significant design factor.

The recommended measurement package concept was developed with the goal of meeting the desired performance and design specifications. These specifications are idealized requirements that have been defined to guide the design of the measurement package system. Based on the analyses performed under this task, it is believed that these design requirements are adequate to meet the baseline objectives of the experiment and are achievable with COTS hardware. However, it should be emphasized that these requirements may be relaxed or strengthened as desired in order to achieve a lower cost or higher performance design, respectively.

4.2 Hardware Package Description and Configuration

A block diagram of the recommended hardware package is shown in Figure 1. Two antennas are used to cover the 100 MHz to 18 GHz frequency range. A right-hand-circularly polarized (RHCP) conical log spiral antenna is used to cover the range of 100 MHz to 1 GHz and a dual linearly polarized log periodic dipole array is used to cover the range from 1-18 GHz. The optimum antenna solution to ensure coverage of all incident signal polarizations (i.e. eliminate polarization mismatch losses for all possible signal polarizations) is to use a dual, orthogonally polarized antenna (such as the dual polarized, log-periodic dipole array) or two orthogonally polarized circular antennas (one RHCP antenna and one left-hand-circularly-polarized (LHCP) antenna). The total field level can be determined by performing separate measurements for each polarization and then appropriately adding the orthogonal polarization electric field components (i.e., forming the square root of the sum of the squares) as part of the post-measurement data calibration process. The drawback to this method is that the measurement scan time will be doubled. Due to size constraints, a COTS orthogonally polarized antenna set could not be identified for the 100 MHz to 1 GHz range. The RHCP antenna was chosen to best match the expected polarizations of VHF and UHF radars that comprise the SSN [7,8,9,10]. This antenna will measure all RHCP signals with no polarization loss and linear polarized signals with approximately 3 dB of loss. However, large polarization mismatch losses will be experienced when trying to measure any LHCP signal. [NOTE: Early in this program it was determined (mostly by discussions with two SSN experts [7,10]) that the VHF and UHF SSN radars have either linear or RHC transmit polarizations. However, it is believed that the Altair site is developing a LHC transmit polarization capability and, late in the program, there was some conflicting information concerning the PARCS site (it may possibly have LHC transmit polarization). If at a later date, it is determined that the inability to measure LHCP over the 100 MHz to 1 GHZ band is unacceptable; a measurement bandwidth trade-off (increase of the lower frequency limit from 100 to 200 MHz) can be made to provide for a system with complete polarization measurement capability. This trade off would still allow for the frequency coverage of all SSN radars. The design modifications would only involve replacing the recommended two antenna, single pole triple throw (SP3T) RF switch system (as shown in Figure 1) with a three antenna, single pole four throw (SP4T) RF switch system. COTS hardware has been identified that can be use to implement this modification.]

The signal levels from the three antenna outputs are measured sequentially by the spectrum analyzer using a mechanical SP3T RF switch. The switch is controlled by the discrete signals available from the EXPRESS Pallet Controller. A 15 dB attenuator is located at the input of the spectrum analyzer. The attenuator protects against possible damage to the spectrum analyzer from large field levels while still permitting the accurate measurement of field levels within the desired dynamic range of the system. The measurement package includes an Ethernet (IEEE 802.3 10BASE-T) GPIB (IEEE 488.2) controller box. This allows the spectrum analyzer, which is controlled using GPIB data bus protocol, to interface with the Ethernet data bus connection provided at the EXPRESS Pallet Controller. Lastly, a 28 VDC to 115 VAC power inverter permits the spectrum analyzer and Ethernet GPIB controller box to be powered from the EXPRESS Pallet 28 Vdc power bus. Relevant information for all the measurement package hardware is listed in Table 1.

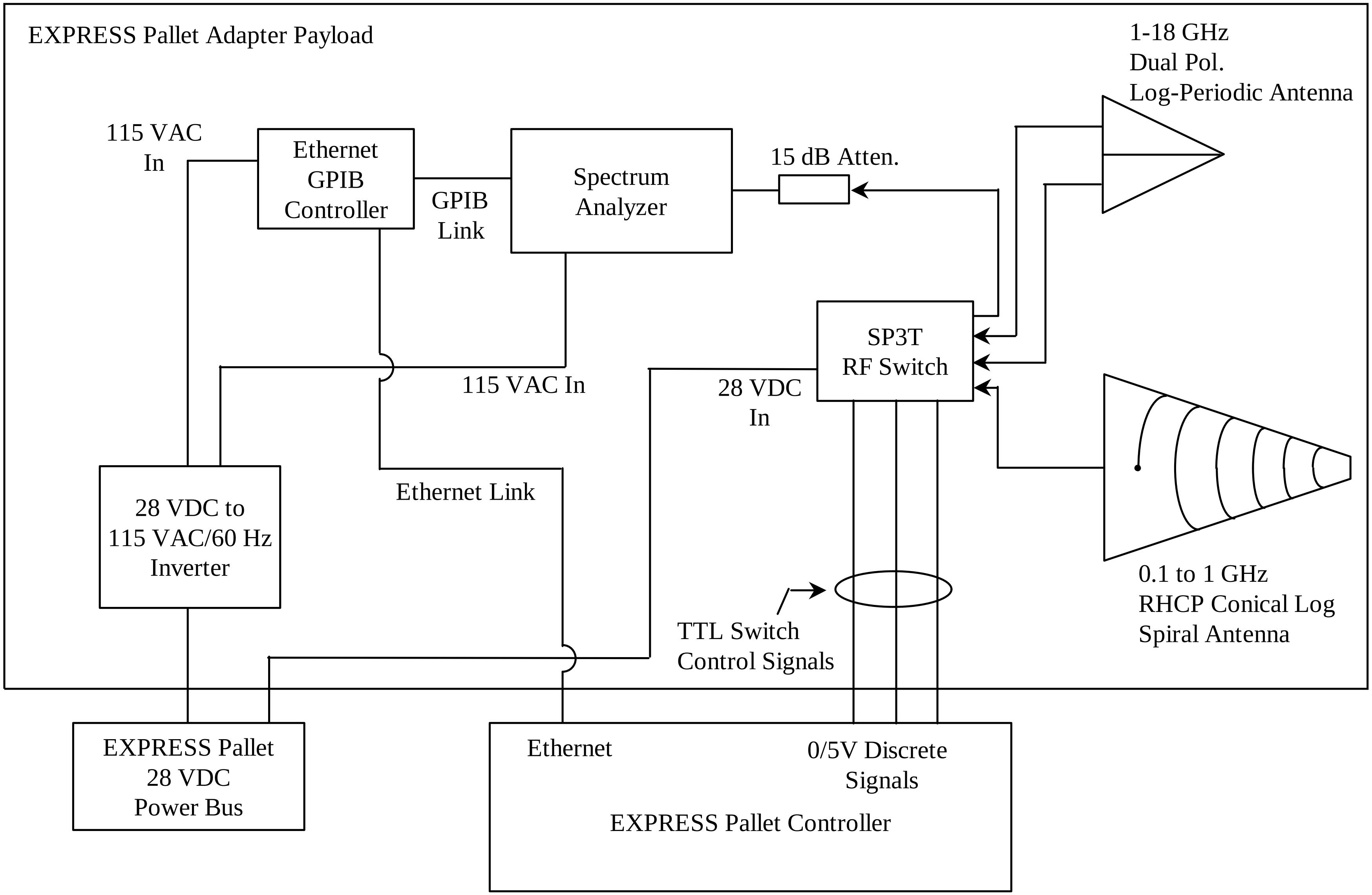

Figure 1: Block Diagram of the E-Field Measurement Package Payload.

Table 1: Measurement Package Hardware Information

Hardware Description	Known Manufacturers	Typical Dimensions (inches)	Typical Weight (lbs)	Typical Power (VA)	Typical Cost**
1-18 GHz Antenna	TECOM	Base Dia.= 8.0 Length = 9.5	4.5	N/A	$3,500
0.1-1 GHz Antenna	EMCO Electro-Metrics	Base Dia = 26.0 Length = 40.0	22.0	N/A	$3,300
Spectrum Analyzer	Hewlett-Packard Tektronix	W =14.0 H = 7.0 D = 17.0	36.0	300.0	$27,000
SP3T RF Switch	Narda	W = 1.8 H = 2.5 D = 1.8	<5.0	4.0	$650
15 dB Attenuator	Narda	L = 5.0	Negligible	N/A	$270
Ethernet GPIB Controller	National Inst.	W = 3.5 H = 1.6 D = 6.0	0.9	8.0	$1,100
28 VDC to 115 VAC Power Inverter	KGS Electronics	W= 6.4 H = 3.5 D = 9.5	4.3	47.0*	$2,100
Misc. Cabling and Connector Adapters	Various	N/A	<10.0	N/A	<$400.0
Totals	--	--	82.7	359.0	$38,320

* Based on the manufacturer's 87% efficiency specification.
** Typical manufacturer's retail cost.

The total equipment package will weigh less than 83 lbs and consume 359 VA of power. Both of these values are well within the limits set for an EXPRESS Pallet Adapter payload. However, it should be noted the total weight does not include support structures that will be necessary for mounting the hardware to the pallet adapter plate. Also, it is expected that additional weight and possibly power consumption will be added due to environmental hardening measures that will be required for operation in the natural space environment. The total measurement package weight and power consumption, including support/mounting structures and environmental hardening measures should still be within the EXPRESS Pallet payload limits.

Figures 2 through 4 shows a canidate layout of the measurement package hardware within the space envelope allotted for an EXPRESS Pallet payload. Again, the support structure required to mount the equipment has not been specified at this time and is not shown in the diagrams. It is recommended that much of the support structure and payload housing materials be fabricated from non-conducting materials to minimize field perturbations and loading effects to the antennas. Equipment layout and mounting will be evaluated during the environmental testing phase of the proof-of-concept tests and may need to be modified based on the results of the testing.

Also, if necessary, some modifications to the specified COTS equipment could be performed to reduce weight and power consumption, and possibly enhance immunity to some environmental effects. Examples of modifications that could be made include removing the spectrum analyzer's CRT and modifying the spectrum analyzer's and Ethernet GPIB controller's power supplies to accept direct dc input. Removal of the CRT would reduce weight, reduce power consumption, and possibly enhance the spectrum analyzer's hardness to vibration and environmental (including EMI) effects. Modification of the power supplies would allow for the use of a dc-to-dc converter (in place of the dc-to-ac inverter) to interface with the EXPRESS Pallet power bus. This would reduce weight and possibly increase power efficiency (although the quoted 87% efficiency specification for the KGS Electronics inverter may be hard to improve upon). Modifications similar to these were made to COTS equipment that comprised an electric field measurement system that has previously flown in space [11].

4.3 Experiment Control and Data Collection

The measurement and data collection process is controlled via the ISS Ethernet data bus. The ISS data bus design includes an Ethernet connection that is provided to the EXPRESS Pallet payloads via the ISS High Rate Data Link (HRDL). This connection will allow the measurement and data collection processes to be controlled by a computer located inside the ISS. It is planned that the U. S. Laboratory will come equipped with a laptop computer that will be dedicated for use with payload experiments. Also, the ISS Ethernet-to-HRDL interface will allow measurement control and data access via the Tracking and Data Relay Satellite System (TDRSS). This will provide for the additional option of controlling the measurement process from the ground, and will also provide a means for downlinking measurement data to earth for analysis.

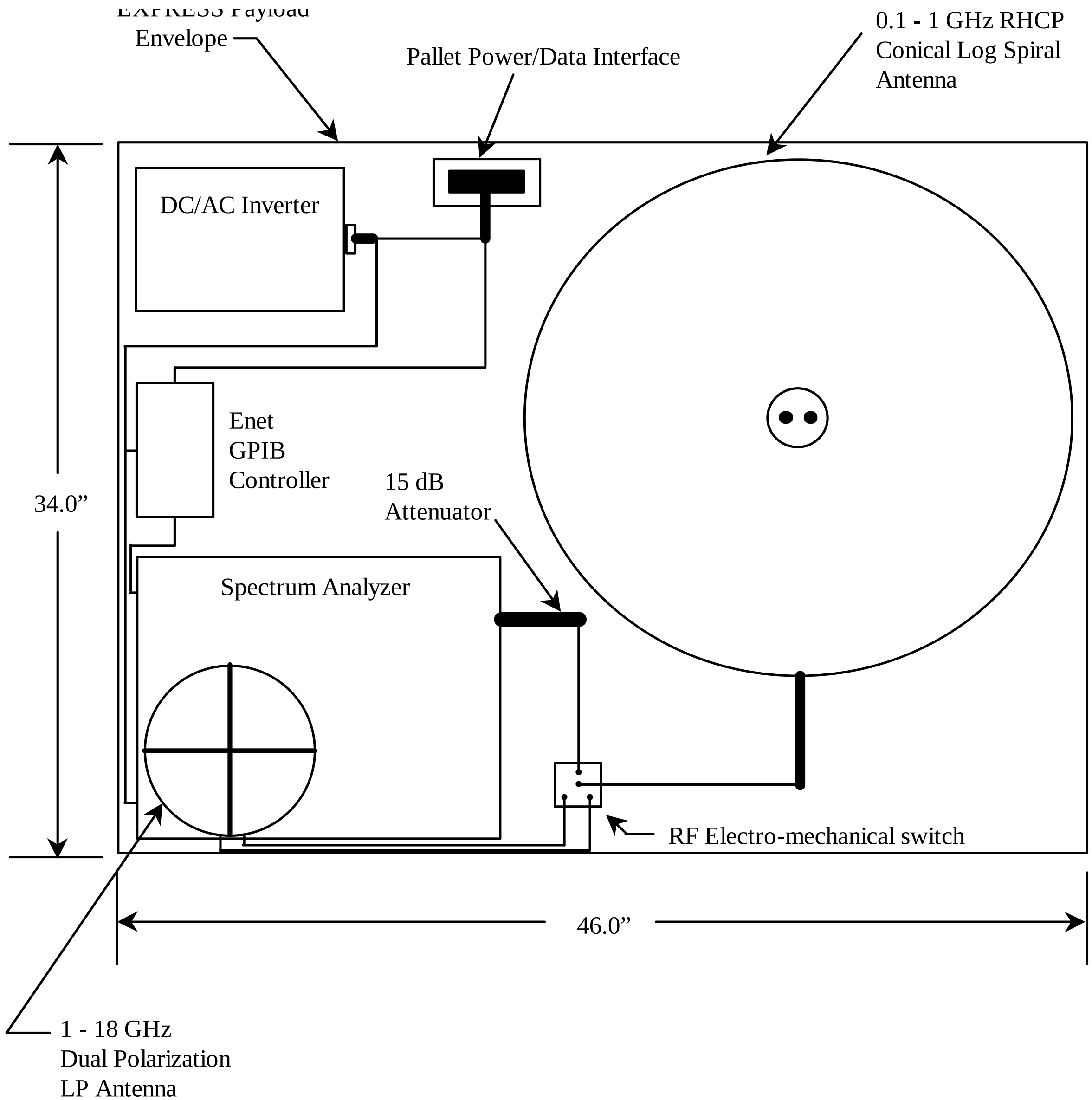

Figure 2: Measurement Package Equipment Configuration (Top View)

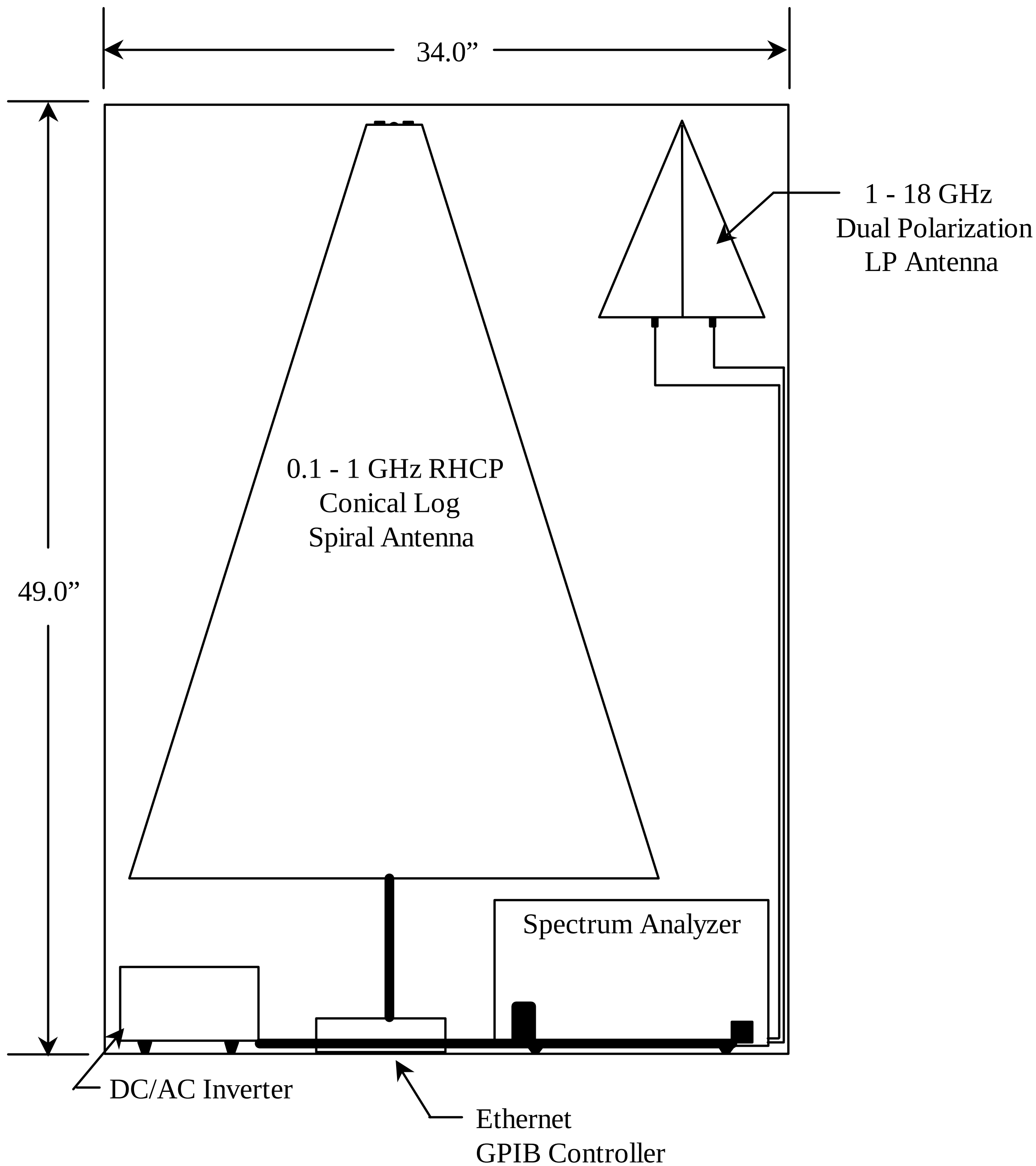

Figure 3: Measurement Package Equipment Configuration (Side View)

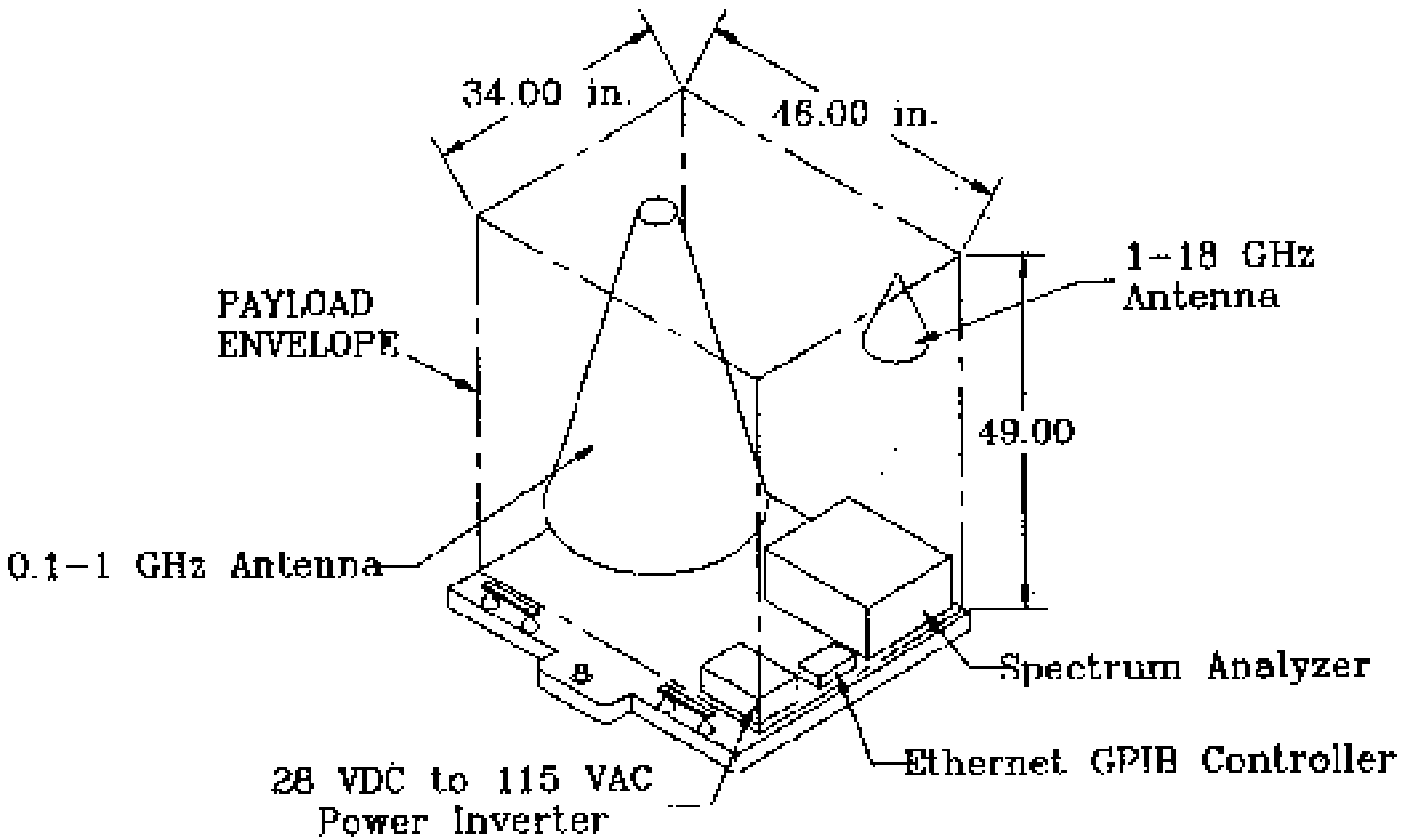

Figure 4: Measurement Package Equipment Configuration (Isometric View)

Implementation of the measurement package will require the development of measurement package control software. The required software can be developed using readily available commercial instrumentation software packages such as LabVIEW®. The software will be based on a detailed software specification that will need to be created early in the course of the measurement package payload development program. Primarily, the software should provide for: (1) remote control of all relevant spectrum analyzer modes and settings (such as resolution bandwidth, video bandwidth, sweep range, sweep time, attenuation, display modes, and measurement units); (2) data collection and storage functions; (3) time and orbital location tagging of collected data; (4) data calibration functions; and (5) system self-test functions. It is possible that additional software will need to be developed in order to interface with the TDRSS. Further investigation will be required to determine the detailed software requirements for ground-based measurement control and data interface capabilities.

5. PROOF-OF-CONCEPT TEST REQUIREMENTS

Upon the initiation of an EFMP payload development program, proof-of-concept testing should be conducted. It is envisioned that this testing would roughly be divided into the categories of operational, environmental, and antenna calibration testing. It should be understood that all testing will be conducted in accordance with detailed test plans that would be created as tasks under the payload development program. Testing details are beyond the scope of this document and only the primary objectives of the tests are described here. Also, it is anticipated that an extensive environmental analysis of the measurement system hardware will be required prior to the performance of environmental testing. The results of this analysis would be used to implement environmental hardening measures and formulate the final mechanical design of the payload package.

5.1 Operational

The purpose of operational testing is to verify the basic feasibility and performance capabilities of the measurement package. Prior to operational testing, the hardware (from Table 1) will be procured and assembled into the recommended measurement package system (as configured in Figure 1). Power and discrete signal inputs will be simulated based on the NASA specifications for the EXPRESS Pallet Controller.

Operational testing will be conducted in two steps. During step one, only manual testing of the system will be conducted (without remote software control) to verify proper operation. The primary objectives of step one testing will be to: (1) verify that the measurement package hardware can be integrated as specified in Figure 1; (2) verify that the system can meet the desired sensitivity and dynamic range specifications; and (3) verify power consumption requirements. The measurement hardware configuration will be finalized upon the successful conclusion of step one testing. Once the specific spectrum analyzer to be used in the system has been chosen, measurement control software development can then be initiated.

Upon completion of the measurement control software, step two testing will be conducted in which the system is tested while under control of the software. The primary objectives of step two testing is to: (1) verify proper operation of the measurement control software; (2) verify the feasibility of Ethernet control of the measurement system; and (3) verify that the system can meet all performance specifications.

In addition, remote control testing must be conducted that will ensure that control of the measurement system is feasible via TDRSS (or other appropriate ground-to-space data links). NASA assets such as TDRSS test sets may be required for this portion of testing.

5.2 Environmental

After operational testing has been successfully completed, environmental qualification analysis and testing will be initiated. Environmental qualification test and evaluation will be conducted (at a minimum) in the following areas: (1) thermal; (2) structural loading and vibration; (3) on-orbit plasma environment; (4) ultraviolet radiation exposure; (5) pressure; (6) atomic oxygen exposure; (7) humidity; (8) ionizing radiation; and (9) electromagnetic interference (EMI).

GTRI conducted a preliminary investigation to determine appropriate environmental test limits and potential environmental hardening measures that are likely to be required to enable the measurement package to operate in the natural space environment. Discussions with ISS thermal environment engineers [12] and applicable documentation [3,5,6,13] were reviewed. At a minimum, the following environmental hardening measures will likely need to be implemented: (1) a heat dissipation system to be used while the system is operational; (2) a heating system to be used when the system is non-operational; and (3) metallic shielding of electronic equipment to mitigate the effects of ionizing radiation (which could also be used for EMI shielding purposes). As was mentioned previously, the specific hardening measures that are required should be determined based on the results of a detailed environmental analysis. An analysis of this type was beyond the scope of the initial concept study, but should be performed as part of the implementation program. This pre-test environmental analysis will be based on the anticipated environmental stresses to the system. The objective of the analysis will be to determine the final mechanical and structural design for the payload package that will permit the measurement system to survive and operate in the external space environment. After the prototype payload package has been fabricated, it will undergo complete environmental testing to verify its qualification to the expected operational environment.

The expected ambient temperature range for a nadir viewing EXPRESS Pallet payload is -120° F to 140° F [12]. Acceptable temperature ranges for all the measurement package COTS hardware has not been identified at this time; however, typical operating temperatures for COTS spectrum analyzers are 32° F to 130° F and storage temperatures typically range from -40° F to 165° F. Also, it should be noted, that the additional heat generated during operation of the system will shift the payload ambient temperature range higher. Thus, it is probable that a payload heat dissipation system will be required during operation of the measurement package and a heating system will be required when the system is non-operational [12]. One of the primary goals of the detailed environmental analysis (to be conducted prior to testing) will be to determine the specific payload thermal conditioning measures that must be implemented to allow the measurement package to function in the on-orbit space environment.

The most severe structural loading and vibration stresses to the EFMP will occur during the lift-off phase of the payload deployment. These stresses greatly exceed the on-orbit stresses (during operation on the ISS) and will be the driver for structural loading and vibration qualification. The launch loading and vibration effects will depend on where the payload is located in the shuttle (Middeck Locker, Mini-Pressurized Logistics Module, etc.). Worst-case load factors for lift-off can be as high as 11.0 g's [6]. Payloads must be designed to maintain positive margins of safety during lift-off. If the measurement package is designed to be returned to Earth in operational condition, load design requirements are even higher (for landing and emergency landing qualification). Guidance for evaluating lift-off loads is provided in NASA Document SSP52005, International Space Station Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures [14]. The measurement package also must be qualified to a vibration environment over the frequency range of 20 to 2000 Hz. Worst-case levels for this environment consist of an acceleration power spectral density of 0.04 g^2/Hz and a composite acceleration of 6.5 g_{rms}. In addition, the measurement package payload must be designed to have a first mode fundamental frequency greater than or equal to 35 Hz

The measurement package payload should be tested to demonstrate survivability in the same neutral atmosphere environment as specified for the EXPRESS Pallet System [13]. The relevant basic requirements for this environment are as follows: (1) the system must meet performance requirements in an on-orbit plasma environment of +40 Volts; (2) the system must meet performance requirements during ultraviolet radiation exposure of 118 W/m^2 for wavelengths less than 0.4 :m; (3) the system must meet performance requirements during exposure to a minimum pressure of $5.5 \cdot 10^{-12}$ psia; (4) the system must operate and meet performance requirements following exposure to a maximum pressure rate change of –0.76 psi per second over a pressure range of 15.2 to $1.94 \cdot 10^{-9}$ psia; (5) the system must meet performance requirements during exposure to atomic oxygen levels of $5.0 \cdot 10^{21}$ atoms/cm^2/year; and (6) the system must be capable of operating and meet performance requirements in an environment of 0% to 100% humidity.

Ionizing radiation consists primarily of high energy charged particles (protons, electrons, and heavy ions) that are produced by several sources including magnetospheric processes, cosmic rays, and solar flares. Effects to electronic equipment are classified as Total Ionizing Dose (TID) effects and Single Event Effects (SEE). SEEs occur as the result of a single ionizing particle interacting with electronic components of equipment. Generally, TIDs and SEEs are estimated as a function of the thickness of the aluminum shielding that is present around the equipment. The ionizing radiation design environment for the ISS is provided in NASA Document SSP 30512, Space Station Radiation Design Environment [15], and should be used (as part of the payload development program) to perform a detailed TID and SEE evaluation (as part of the overall environmental analysis). In addition, recommended test levels for SEEs are specified in NASA Document SSP 30513, Space Station Ionizing Radiation Effects Test and Analysis Techniques [16]. As was mentioned previously, it is anticipated that shielding measures will have to be implemented for COTS equipment to survive in the natural space environment. Specific shielding measures will be determine based on the results of the pre-test analysis.

The measurement package must demonstrate compliance with the conducted and radiated emissions requirements specified in NASA Document SSP 30327, Space Station Electromagnetic Emission and Susceptibility Requirements for EMC [3]. Also, conducted and radiated susceptibility testing should be performed on the measurement package. The radiated susceptibility testing should be performed with the antennas removed and the RF input to the spectrum analyzer terminated with a 50 ohm load. Normally, non-safety critical payloads are tested to the RS03PL limit which ranges from 5 V/m to 60 V/m over a 14 kHz to 15.2 GHz frequency range. However, because the measurement package must be able to measure field levels up to 250 V/m, the radiated susceptibility test limit should be tailored in both amplitude and frequency to verify satisfactory performance in the anticipated electromagnetic environment. Equipment aluminum shielding that is implemented to protect against ionizing radiation effects can also serve to harden the equipment against EMI effects provided that care is taken to treat all enclosure apertures and penetrations (gasketing, filtering, etc.).

5.3 Antenna Calibration

After the measurement package payload mechanical design has been finalized and qualified to the its operational environment, antenna calibration should be performed. All antenna measurements and calibration will be conducted with the antennas mounted in the measurement package as they will be when on-orbit. The antenna calibration will consist of two parts: (1) measurement of basic antenna parameters (such as patterns, beamwidth, gain, and VSWR); and (2) calculation of far-field antenna factors. The objective of the basic antenna parameter measurements is to determine if the packaging of the antennas (as they are located in close proximity to each other and the other system components) is inducing any unacceptable pattern corruption or VSWR degradation effects. As previously mentioned (Section 4.1), if the EFMP is located inside the ISS U. S. Laboratory, the antennas should be "hooded" and mounted to the 20 inch diameter window. In this case, all antenna measurements should be performed on the hooded antennas with a mock-up of the 20 inch window mounting assembly.

Far-field antenna factors are used to convert the measured voltage levels to electric field strength values (in volts per meter). The antenna factors will be calculated as a function of frequency from the measured far-field gain and pattern data. The measurement system software will use the antenna factor data (along with cable and switch loss data tables) to perform the electric field strength calibration.

6. ON-ORBIT EXPERIMENTAL PROCEDURES

6.1 Set-Up Procedures

Hardware set-up procedures will not be required for the measurement package since all the system hardware will be pre-packaged as an EXPRESS Pallet payload. There may be some set-up required to install the system control and data bus interface software on the controlling computer (on the ISS and/or the ground). Specific procedures for software set-up should be determined in the final stages of the payload development program.

6.2 Self-Test and System Start-Up Procedures

After initial installation of the measurement package system, a self-test will be required to ensure that the system is operating properly. Detailed self-test procedures should be developed as part of the payload development program. It is envisioned that the self test will be automated and run upon system power up and as an option under the system control software. The system self-test will: (1) verify that the Ethernet GPIB controller and spectrum analyzer are powered; and (2) verify that all software controllable spectrum analyzer modes and functions are operating properly. Additional self-tests should be performed to verify that the RF electro-mechanical switch is operational. This may be accomplished, in part, by verifying the presence of return current for each 5 volt discrete switch control signal (provided form the EXPRESS Pallet controller), as the switch control signals are activated in sequence. Other procedures to verify proper switch operation could involve the use of on-board transmitters. The use of at least two on-board transmitters would be required: one that transmits in the frequency range of 100 MHz to 1 GHz and another that transmits in the frequency range of 1 to 18 GHz. Switching between the two EFMP antennas could be verified by observing a significant reduction in signal level when the output of the out-of-band antenna is switched to the spectrum analyzer input.

It is recommended that field levels for specific high level ISS on-board transmitters should be measured after initial start-up of the system. This will involve a coordinated test in which the transmitters will be activated specifically to allow measurement of its field level at the measurement package payload location. Field level data (both frequency and magnitude information) for these on-board transmitters will be documented and later used in the data analysis process to help differentiate on-board signals from ground-based emitter signals.

6.3 Data Collection Procedures

The system measurement control software must allow considerable flexibility in the data collection process. All significant measurement parameters (such as resolution bandwidth, video bandwidth, sweep range, sweep time, etc.) should be selectable by the user. However, the default mode for data collection should be tailored to measure ground-based radars and to systematically collect data over the complete 100 MHz to 18 GHz using a nominal resolution bandwidth of 3 MHz. The basic default data collection procedure will be as follows: (1) switch to the 100 MHz to 1 GHz antenna output; (2) perform scan over the 100 MHz to 1 GHz band; (3) switch to the Number 1 output on the 1 to 18 GHz antenna; (4) perform scan over the 1 to 18 GHz band; (5) switch to the Number 2 output on the 1 to 18 GHz antenna; (6) perform scan over the 1 to 18 GHz band; (7) save data to a permanent storage location (save to internal ISS computer hard disk and/or EXPRESS Pallet controller data buffer). The minimum sweep time (to allow intercept of radars with PRFs greater than 100 Hz) is 3.3 ms/MHz. The total time required to perform the procedure described above and collect one complete set of data for the entire 100 MHz to 18 GHz frequency range will be approximately two minutes.

6.3.1 Number Orbits Required for Data Collection

Based on a nominal 90 minute orbital period, successive ground tracks will be separated by approximately 22.5 degrees in longitude. With an orbital inclination of 51.6 degrees and a 200 nmi orbital altitude, all SSN emitters with latitudes between approximate 65 degrees N and 65 degrees S should be able to have line-of-sight (LOS) visibility to the ISS. Of the 17 radars that make up the U.S. SSN, only one (BMEWS I) will not have LOS visibility to the ISS.

SSN radar metric observations include time, elevation, azimuth, range, and possibly range rate [10]. Three to five metric observations are typically made per track and six to ten seconds are typically required per metric observation. Thus, track times are expected to be in the 18-50 second range. As detailed in Section 3.7, spectrum analyzer scan times of approximately 60 seconds per polarization (or 120 seconds total for two orthogonal polarizations) are required to scan the entire 100 MHz to 18 GHz frequency range. However, spectrum analyzer scan times can readily be reduced below 18 seconds while still ensuring intercept of radar pulses by narrowing the scan frequency range about the known operating frequency of the tracking radar. Also, longer track times could presumably occur provided that special arrangements are made in advance. In either case, if the ISS is tracked by a SSN radar, it can be assumed that electric field data can be collected from that SSN radar.

According to Reference 10, standard procedure for tracking the ISS would consist of at most a single SSN radar track per orbit (provided LOS visibility exists). Furthermore, without special arrangements being made, it is likely that certain SSN assets would be used to track the ISS more often than other assets. For example, all else being equal, UHF phased array radars would likely be the asset of choice (in favor of UHF or C band dish radars) due to the higher achievable data rates. With 16 radars in the U.S. SSN with LOS visibility to the ISS and without special arrangements being made to ensure that specific assets are used to track the ISS, an inordinately high number of orbits would be required to ensure that all SSN radar emissions are characterized. Thus, it is assumed that special arrangements will be made in advance of the experiment to allow for tracking of the ISS with specific radars during specific times and orbits and, if desired, tracking of the ISS by more than one SSN radar in a single orbit. Assuming that these prior arrangements will be made and allowing for the possibility of some orbits in which the ISS will not be visible to a SSN radar or will only be visible to a radar which has already be characterized, it is estimated that a minimum of about 10 orbits will be required to characterize the emissions from the SSN. A greater number of orbits are desirable to provide better statistical data on SSN radars and other emitters.

7. REFERENCES

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